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Hypervelocity Launcher for Aerothermodynamic Experiments – Phase 2

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Final Report

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FORWARD

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INTRODUCTION

1.1 BACKGROUND

Hypersonic aerospace vehicles are subjected to extremes in temperature and pressure during atmospheric flight. The development of hypersonic aerospace vehicles requires detailed knowledge of the aerothermodynamic (ATD) environment in which the vehicles will operate. Also, the design of orbital transfer and interplanetary spacecraft which use aerobraking requires detailed information about ATD conditions.

Experimental data relevant to hypersonic ATD conditions is very difficult to obtain. The regime of interest consists of high flow velocities (greater than 5 km/s and up to 15 km/s) in real gases (such as air) at high pressures (i.e., atmospheric pressure). Making matters difficult is the need for quasi-steady flow conditions to adequately characterize the turbulence and heating associated with hypersonic flight. Lastly, large scale test articles (0.5 m or larger) are required to avoid the small shock standoff distances associated with small test articles. The only experimental technique presently capable of achieving the required ATD conditions is a flight vehicle in earth reentry. Instrumentation and data recording/retrieval for this type of experiment is difficult and very expensive.

A terrestrial based alternative to flight tests, which can achieve the required flow conditions, is highly desirable. Two launcher types, light gas and electromagnetic (EM), have been contemplated for this ballistic test facility. Light gas guns are fundamentally limited to launch velocities in the 5 to 7 km/s regime due to the sonic velocity of the gas. No such fundamental limit exists for EM launchers. EM launchers have the theoretical potential for high velocities (>10 km/s) and high efficiency (>75%). EM launchers can also be scaled to the large bore sizes required for ATD testing.

Research on EM launcher technology has been intensive in recent years. Realization of the theoretical potential for this technology has been elusive. There are several deficiencies which must be overcome before development of launchers for hypervelocity ATD testing and other high velocity applications may proceed. Specifically, the three key deficiencies are; a lack of hypervelocity performance (i.e., >6 km/s), a lack of high energy efficiency, and a lack of compact power supplies.

This program addressed all three key issues via the development of an Ultra Distributed Energy Store System (UDESS) to power an EM launcher. A UDESS uses many closely spaced power supplies to provide the accelerating current for the launch package. Figure 1 shows a simplified

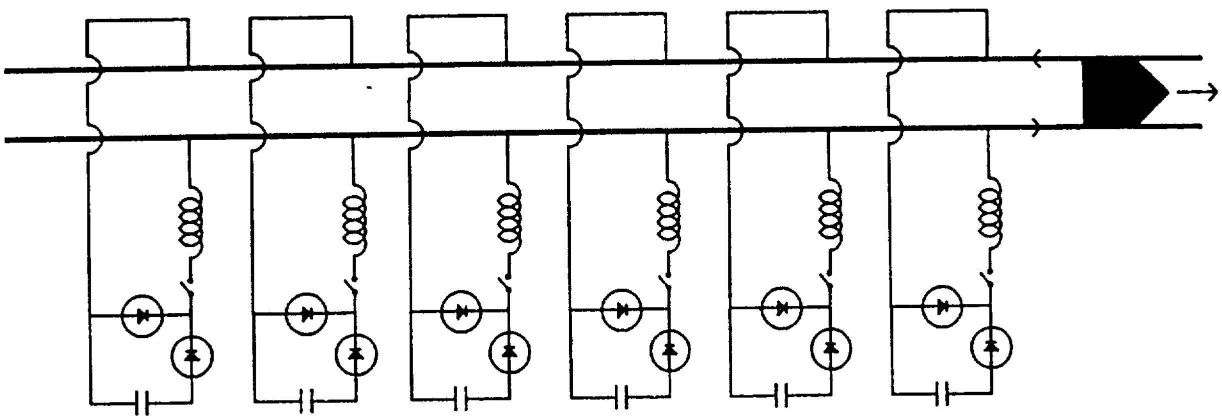

Figure 1. A simplified schematic of a UDESS electromagnetic launcher.

electrical circuit showing several of these power supplies connected to the rails of the launcher. The UDESS system is controlled such that, during the launch, only a small number of power supplies, those in close proximity with the armature, are providing current to the launcher. The effect is that each supply is providing power to only a short section of the launcher. This effectively lowers the launcher impedance and results in a lowering of the rail-to-rail voltage developed at each supply.

The reduction of the rail-to-rail voltage gives the UDESS the potential for achieving hypervelocity performance. To date, the highest velocities in EM launchers have been achieved using plasma armatures, where the plasma is typically initiated at the start of the launch by fusing a small amount of copper behind the launch package. The ideal plasma armature provides a compact high current conduction path directly behind the launch package, resulting in high acceleration force. It is generally believed that secondary current paths in the plasma, which reduce the accelerating current in the main armature, are responsible for low velocity in EM launchers. These secondary armatures form when the plasma fails to remain compact and when there is a high rail to rail voltage at some distance behind the main armature. The UDESS launcher reduces the rail to rail voltage behind the main armature and therefore prevents the formation of secondary plasma armatures.

The UDESS EM launcher also has increased system efficiency over conventional EM launchers through reduced rail losses and reduced stored energy in the barrel. The increased efficiency allows for a smaller overall power supply volume. Also, the distribution of the supply currents lowers the EM forces in each supply, enabling a less massive power supply structure.

In our Phase I effort, we successfully demonstrated the feasibility of the UDESS concept. We determined the requirements for both rail-to-rail voltage and efficiency. In order to prevent secondary current paths, the rail-to-rail voltage needs to be less than 40 V/mm at a distance no closer than 15 bore diameters from the rear of the projectile. To show an improvement over present breech fed railgun systems, the efficiency needs to be greater than 30% (the highest efficiency of present plasma armature railgun systems). We experimentally validated our models for UDESS operation with a four stage test launcher. We also began work on the design tools required for full scale system development. The success of our Phase I effort indicated that this technology was ready for larger scale development in Phase II.

1.2 PHASE II OBJECTIVE

Our Phase II objective was to experimentally assess the capability of an Ultra Distributed Energy Store System (UDESS) powered EM launcher. Our goal was to develop the technology base and demonstrate an electromagnetic launcher system capable of achieving repeatable, high velocity (>6 km/s) launches. This goal was to be attained by demonstrating that the UDESS was effective at reducing secondary current paths by reducing the rail-to-rail voltage behind the main armature.

1.3 SUMMARY OF TECHNICAL ACHIEVEMENT

IAP Research Inc. has successfully developed and tested a UDESS powered electromagnetic launcher. The prototype UDESS launcher is shown in Figure 2. This launcher consists of three accelerating stages; a light gas injector, a breech-fed EM pre-accelerator, and the UDESS. The launcher shown in Figure 2 was configured for an eight stage DES launch. With the prototype launcher we performed numerous experimental launches.

The UDESS system was developed specifically to address the velocity speed limit seen in plasma armature EM launchers. During the course of this program both plasma armature and metal armature launch packages were developed and tested. Under our initial program plan only plasma armature testing was to be completed. We tested metal armature launch packages to assess the usefullness of the UDESS concept for low velocity applications.

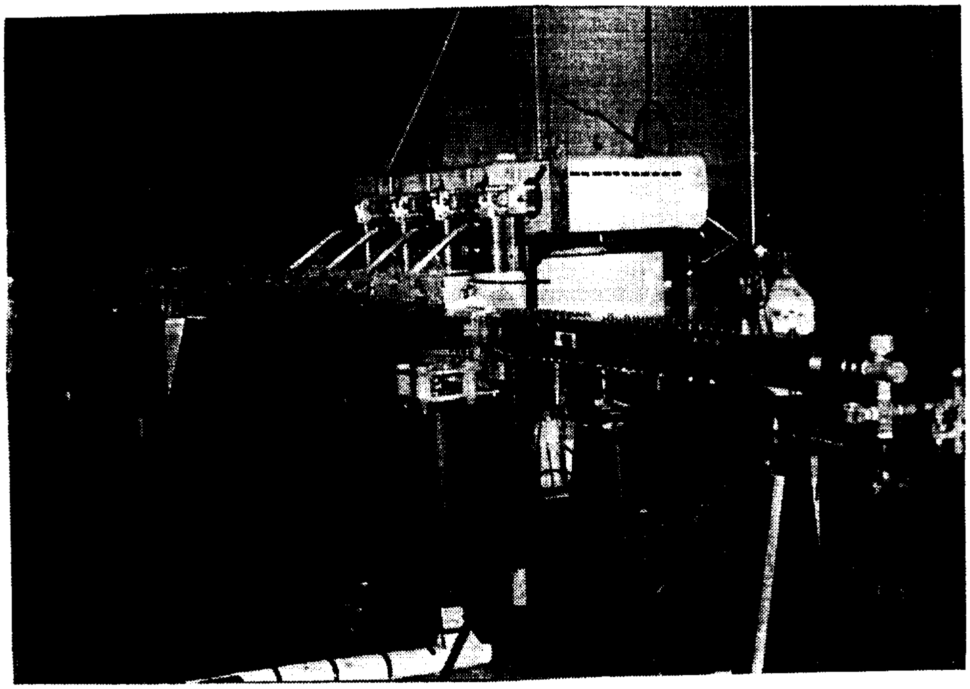

Figure 2. The prototype UDESS EM launcher.

A summary of the tests completed during this program is listed in Table 1. Overall, the performance of the UDESS launcher was disappointing. The development of the UDESS launcher proved to be quite difficult. While we did ultimately achieve our goal of performing controlled UDESS launches, but we were not able to achieve our goal of reliable high velocity launches. The launcher, as conceived and developed for this program, appears to have a detrimental effect upon plasma armatures. The results of the metal armature launches were more positive, but more testing/tuning is required to show benefit of the UDESS system over a standard breech-fed launcher.

TABLE 1. SUMMARY OF PROTOTYPE UDESS LAUNCHER TESTS

Description	Launch Package	UDESS	Result
1. Baseline launch	Injected plasma 5 g	4 supplies not connected.	Good launch.
2. Baseline launch	Injected plasma 5 g	4 supplies connected but disabled.	Good launch. Long armature observed
3. UDESS launch	Injected plasma 5 g	4 supplies enabled.	Good launch. Distinct secondary formation due to projectile breakup. Supplies fire in proper sequence.
4. Baseline launch to test projectile.	Injected plasma 5 g	4 supplies disabled.	Projectile appears to break up again. Distinct secondary formation.
5. Baseline launch	Injected plasma 10 g	4 supplies disabled.	Good launch. Some problems with the data acquisition system causes loss of data.
6. Baseline launch	Injected plasma 10 g	4 supplies disabled.	Good launch.
7. UDESS launch	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate. All data acquired is corrupted.
8. UDESS troubleshooting	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate properly.
9. UDESS troubleshooting	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate properly.
10. UDESS launch	Injected plasma 10 g	4 supplies enabled.	Good launch.
11. UDESS launch	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate properly.
12. UDESS launch	Injected plasma 10 g	4 supplies enabled.	BJ bank prefires, destroys breech.
13. Baseline launch	Stationary metal	4 supplies disabled.	Good launch.
14. Baseline launch	Stationary metal	4 supplies disabled.	Good launch.
15. UDESS launch	Stationary metal	4 supplies enabled.	Good launch.
16. UDESS launch	Injected metal	4 supplies enabled.	Good launch.
17. Armature test with BJ ripple fire	Stationary metal	Supplies disabled.	BJ ripple incorrect. Armature transitions. Range severely damaged.
18. Armature test	Injected metal	4 supplies enabled.	BJ delay incorrectly set. Launcher damaged in area of breech.
19. Armature test	Stationary metal	Supplies disabled	Good launch.
20. Armature test	Stationary metal	Supplies disabled.	Good launch.
21. Armature test	Injected metal	Supplies disabled.	BJ bank prefires causing severe damage to the launcher.
22. Armature test	Injected metal	Supplies disabled.	BJ bank prefires causing severe damage to the launcher.
23. Armature test	Injected metal	Supplies disabled.	Good launch.
24. Armature test	Injected metal	Supplies disabled.	Good launch.
25. Baseline launch	Injected plasma 10 g	8 supplies disabled.	Good launch.
26. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Good launch, some data acquisition problems.
27. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Launcher voltage breakdown, some UDESS supplies do not fire.
28. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Good launch.
29. UDESS launch	Injected plasma 10 g	8 supplies enabled.	BJ bank module fails, some UDESS supplies do not fire.
30. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Good launch, some data acquisition problems.
31. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Strong secondary armature formation, UDESS controls do not trigger.

Although we failed to achieve our performance goals for this program, we now have a strong understanding of the effects of the UDESS. We believe that the concept still has merit but that it will require additional development before it can successfully overcome the velocity speed limit. Additionally, we increased our level of understanding of plasma armature launch mechanisms which will benefit the entire EM launcher community. Overall, we significantly advanced our understanding of EM launcher performance and design and we believe that the knowledge gained during this program will be of great benefit towards the development of future EM launchers.

1.4 TECHNICAL APPROACH

Our technical approach consisted of five key elements which remained constant throughout the program. These key elements were as follows:

- Task 1— System Modeling. We modeled the ideal response for the launcher passed upon software developed in Phase I. The modeling results were used as a guide for the system design task.
- Task 2 — System Design and Integration. With completion of this task we had a complete system design and system integration plan.
- Task 3 — Fabrication and Assembly. Under this task the prototype UDESS launcher system was fabricated and assembled, including all controls and diagnostics equipment.
- Task 4 — Performance Testing. The objective of this task was to characterize the performance of the UDESS launcher and launch packages through testing.
- Task 5 — Performance Analysis. Under this task the results of performance tests were analyzed to determine the effects of a UDESS EM launcher upon plasma armatures.

1.5 REPORT SUMMARY

This report is the Final Report for the Phase II effort to develop a Hypervelocity Launcher for Aerothermodynamic Experiments. This report is broken into six sections. The first section is this introduction.

Section 2 — *Hypervelocity Launcher Significance and Technical Objectives* examines in detail the significance of hypervelocity launchers for aerothermodynamic experiments and the application of EM launchers to a terrestrial based test facility. The UDESS EM launcher is introduced and the technical objectives for its development program are presented.

Section 3 — *Development of the UDESS Electromagnetic Launcher* examines the detail design of prototype UDESS launcher. In this section we describe: the key design issues, the technical problems associated with each, and the methods and solutions used to resolve these problems.

Section 4 — *UDESS Prototype Launcher Performance Tests* describes the hardware and procedures used to measure the performance of the prototype UDESS electromagnetic launcher. In this section we present a summary of the tests which were performed on the UDESS launcher and subsystems.

Section 5 — *Discussion of UDESS Performance and Results* we give the results of analysis on the UDESS experiments and discuss the system performance.

Section 6 — *Conclusions and Recommendations* completes this report.

SECTION 2

HYPERVELOCITY LAUNCHER SIGNIFICANCE AND TECHNICAL OBJECTIVES

2.1 SIGNIFICANCE OF AEROTHERMODYNAMIC EXPERIMENTS

Hypersonic aerospace vehicles are subjected to extremes in temperature and pressure during atmospheric flight. The development of hypersonic aerospace vehicles requires detailed knowledge of the aerothermodynamic (ATD) environment in which the vehicle will be operated. Orbital transfer and interplanetary spacecraft using aerobraking also require detailed information of ATD conditions for design. ATD conditions which require characterization include real gas dissociation, ionization, chemical reaction kinetics, and shock turbulence interactions. Both analytical and experimental data are required to develop the database for design. Analytical techniques can be used to study a broad range of conditions, while experimental techniques are required to validate the models at specific conditions. Experimental techniques are also needed to obtain fundamental fluid dynamic properties at temperature and flow conditions, heretofore, not measured.

Terrestrial based ballistic testing is the only alternative to flight tests for achieving the required flow conditions. The two launcher types that may be contemplated are light gas guns and electromagnetic guns. Light gas guns are limited to launch velocities in the 5 to 7 km/s regime. No such fundamental limitation on launch velocity exists for electromagnetic guns. Electromagnetic (EM) launchers therefore appear to be an option for creating the required flow conditions. However, EM launchers of any size have not yet achieved the required performance levels.

2.2 APPLICATION OF ELECTROMAGNETIC LAUNCHERS FOR AEROTHERMODYNAMIC EXPERIMENTS

Electromagnetic launchers are being developed for hypervelocity aerothermodynamic testing, earth-to-space launch, equation-of-state materials testing, strategic missile defense, small and large caliber tactical weapons, and lethality testing. This broad set of applications translates to a broad and diverse range of performance requirements. Bore size, muzzle energy, launch velocity, fire rate, barrel life, and system size/mass are but a few of these important requirements. Considerable progress has been made in railgun technology-base and system integration development. Large and small scale demonstrators are now under testing at multiple facilities across the U.S., and indeed at several locations in the free world. EM launcher technology will continue to evolve as a result of these ongoing efforts.

EM launchers have the potential for high velocities (>10 km/s) and high efficiency (>75%). EM launchers can also be scaled to the large bore sizes required for ATD testing. One major advantage of EM launchers over other alternatives is the ability to select the acceleration profile. This is done by customizing the accelerating current wave form used to launch the test article. No other launch alternative has this capability. EM launchers can also be designed and constructed in a modular fashion, allowing large systems to be built up from smaller more manageable modules. EM launchers have a great deal of promise, but like all new technologies, there are development hurdles which must be overcome in order for the promise to be fulfilled.

Advances have been secured in several technology areas. These include lightweight and stiff barrels, improved barrel materials, improved switches and power supplies, better armatures, and lightweight high gee tolerant projectiles/launch packages. These improvements make demonstrator construction possible.

Despite these technology advances made so far, several deficiencies hamper full scale EM launcher system development for hypervelocity ATD testing and other high velocity applications. Three of these key deficiencies are: lack of hypervelocity performance (i.e., > 6 km/s), lack of high energy efficiency, and lack of compact power supplies. For nearly all EM launcher applications, low efficiency and large power supply size are deterrents to faster adoption and development. All three deficiencies are important for ATD testing and earth-to-space launch missions.

2.2.1 The Velocity Limit in Electromagnetic Launchers

Numerous railgun experiments have been conducted with the goal of reaching velocities of 10 km/s or more.[1,2,3] The results have been similar. At modest velocities (up to about 3.5 km/s), railguns operate with very nearly theoretical performance ($v = L' \int (I^2 dt/2m)$). As the velocity increases, the performance deviates more and more from theoretical predictions. As 6 km/s is approached, the deviation increases such that the velocity remains fixed at about 6 km/s (or less)

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1. D. E. Brast and D. R. Sawle, "Feasibility Study for Development of a Hypervelocity Gun," MB-R-65/40, N65-24359, May 1965.

2. C. S. Rashleigh and R. A. Marshall, "Electromagnetic Acceleration of Macroparticles to High Velocities," J. Appl. Phys. 49(4), April 1978.

3. R. S. Hawke, et al, "Summary of EM Launcher Experiments Performed at LLNL," IEEE Trans on Mag, Vol. MAG-22, No. 6, pp 1510-1515, November 1986.

independent of energy input or barrel length. In other words, there is a velocity limit at 6 km/s that has so far been an impediment to further railgun hypervelocity progress.

The velocity limit is now widely conceded to be the result of current being shunted from the main armature into secondary armature(s) behind the main armature. The secondary current front(s) travels at a lower velocity than the main armature and becomes more and more separated from it. The current flowing in the secondary armature does not contribute to launch package acceleration. In fact, the secondary current dramatically reduces launch package acceleration. The accelerating force is proportional to the square of armature current, so for example, if a secondary current contains only 20% of the total gun current, the launch package accelerating force is reduced by 36%.

The physics governing secondary conduction has become increasingly clear. Secondary conduction is the result of interactions between the plasma armature and the bore. There are two major contributing factors to secondary conduction. First, plasma armatures ablate the bore walls and plasma leaks back into the bore. Plasma is lost from the main armature via boundary layers and instabilities, and the region behind the main armature becomes filled with plasma. This plasma is highly conductive. Conductive plasma in the bore behind the main armature is not a problem by itself. However, when put together with the fact that there is a voltage across the rails behind the armature, the picture is complete. The high rail-to-rail voltage forces current flow through the conductive plasma left behind by the main armature.

2.2.2 Rail-to-Rail Voltage for a Breech Fed Railgun

Figure 3 shows a schematic of a normal breech fed railgun. This railgun gets all its energy from one or more power supplies fed to the gun at the breech. The voltage, V_b, at the breech of the railgun is:

$$V_b = V_{arm} + IR'x + d\phi/dt \tag{1}$$

where V_{arm} = voltage drop across the armature,

I = current through the armature,

R' = rail resistance gradient,

x = distance from the breech (or power supply feed point) to the armature, and

$d\phi/dt$ = time rate of change of magnetic flux in the barrel.

Now $d\phi/dt$ is:

$$\frac{d\phi}{dt} = \frac{d}{dt}(L'xI) = L'x\frac{dI}{dt} + L'\frac{dx}{dt}I \qquad (2)$$

where L' = barrel inductance gradient.

Since dx/dt is just the velocity, v, Equation 1 becomes:

$$V_b = V_{arm} + IR'x + L'x\frac{dI}{dt} + L'vI \qquad (3)$$

As the velocity of the armature increases, the L'vI term quickly becomes the dominant term and the breech voltage increases. The only term that can be negative is the L'xdI/dt term due to a declining current, I, (i.e., negative dI/dt). However, in a breech fed railgun, dI/dt is usually small in magnitude

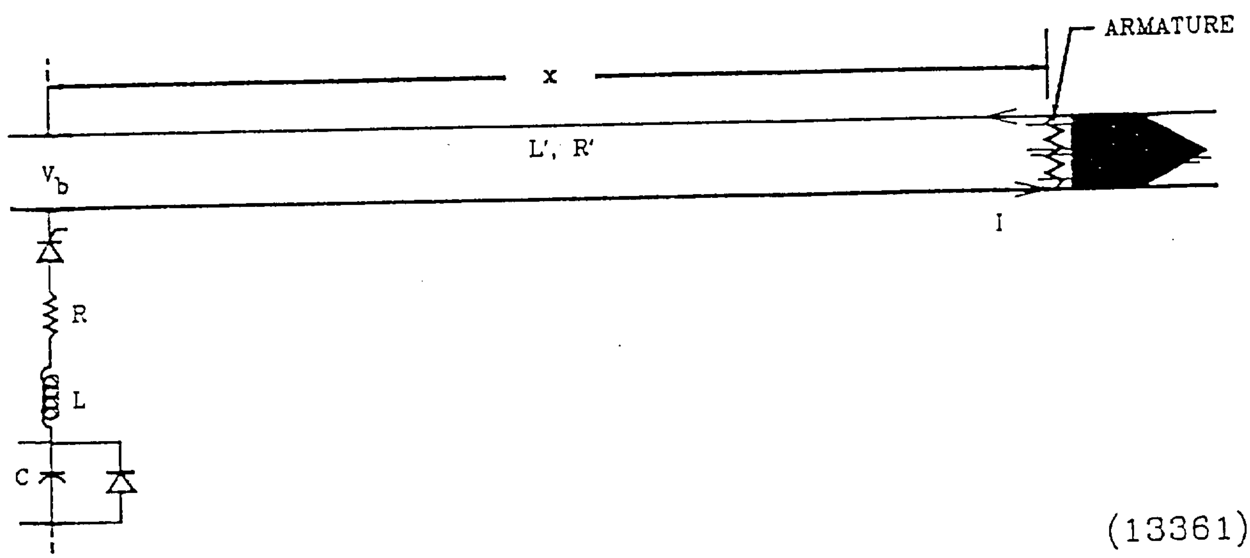

Figure 3. A conventional breech fed electromagnetic launcher.

since the usual goal is to launch the projectile at nearly constant, high acceleration in order to reduce barrel length.

The rail resistive voltage drop increases with distance back from the main armature. The back EMF increases approximately linearly with velocity. The armature voltage drop is constant and, at high velocities, is small compared to the other two voltage components. The result is that the rail-to-rail voltage increases, at least linearly, with velocity. It is not surprising then that secondary conduction increases with velocity and the loss of accelerating force worsens as velocity rises.

Apparently, by 6 km/s, the secondary conduction has reduced the current in the main armature to the point where it cannot overcome drag. Thus, a velocity limit is reached.

With the cause of the velocity limit clear, solutions also become clear. As there are two main contributing factors to the formation of secondaries, there are also two main approaches we can take in solving the problem: (1) reduce or eliminate the residual plasma (or at least reduce the conductivity of the residual plasma), and (2) reduce or eliminate the rail-to-rail voltage.

2.2.3 Railgun Efficiency

Efficiency is another major problem with railgun performance. Railgun efficiency (defined as the ratio of launch package muzzle kinetic energy to stored electrical energy) is predicted to be in the 20 to 40 percent range for most applications with conventional railguns. However, the highest reported actual performance efficiencies are only around 28 percent for plasma armatures. These relatively low efficiencies mean that the power supply must generate from 2.5 to 5 times the required kinetic energy. To compound the problem, some of the wasted energy is dissipated ohmically and must be removed from conductors by a thermal management system. Low railgun efficiency, therefore, leads to sizable power supplies and large thermal management systems.

The low efficiency associated with breech fed railguns can be traced to two main sources: the energy loss due to rail resistance ($I^2R'x$); and the residual magnetic energy left in the barrel when the projectile exits ($\frac{1}{2}L'xI^2$). We can increase the efficiency of a railgun by decreasing one or both of these losses.

A conventional railgun is powered from the breech. In order to obtain short barrels, the power supply is designed to provide high current (and therefore maintain high accelerating force) throughout the launch. Substantial magnetic flux is stored in the barrel due to the high rail currents. Most of the wasted energy in a railgun shot results from residual magnetic flux stored in the railgun barrel at the end of launch. This magnetic flux is very difficult to recover, and usually ends up dissipated ohmically in the rails and in a muzzle arc.

2.3 THE ULTRA DISTRIBUTED ENERGY STORE SYSTEM (UDESS) ELECTROMAGNETIC LAUNCHER.

A UDESS uses many closely spaced power supplies to provide the accelerating current for the launch package. At any time during the launch, several power supplies provide current to the armature. After the launch package passes a charged power supply by a prescribed distance, the switch for that supply is closed causing current to flow from that supply, through the armature. The individual contributions of several supplies combine to give the total accelerating current for the launch package. As the launch package accelerates away from a power supply, the current from that supply decays exponentially.

A UDESS has the potential for achieving hypervelocity performance by preventing secondaries through reduction of the rail-to-rail voltage. A UDESS also has the potential for increasing the efficiency of EM launchers. The UDESS decreases the system losses by decreasing the length of barrel that is powered.

2.3.1 Rail-to-Rail Voltage for a UDESS Railgun

Figure 4 shows a schematic of a two-stage UDESS railgun. Unlike a normal breech fed railgun, a UDESS railgun has energy stores placed all along the barrel. Each energy store connects to the rails at some distance from the breech. With only one energy store in operation, the voltage at the breech is the same as for a normal breech fed railgun (Equation 4). With two energy stores in operation as shown in Figure 4, the voltage, E_2, at any position from the armature back to the active energy store closest to the armature is:

$$E_2 = V_{arm} + R'x(I_1 + I_2) + L'v(I_1 + I_2) + L'x\frac{d}{dt}(I_1 + I_2) \tag{4}$$

where I_1 = current from Energy Store 1, and

I_2 = current from Energy Store 2.

The voltage, E_{1-2}, at any position between the two active energy stores is:

$$E_{1-2} = E_2 + R'sI_1 + L's\frac{dI_1}{dt} \tag{5}$$

where s = distance from Energy Store 2 to the measuring point.

The voltage, E_1, at any position from the breech up to the active energy store farthest from the armature is:

$$E_1 = E_2 + R'\ell I_1 + L'\ell \frac{dI_1}{dt} \tag{6}$$

where ℓ = distance between energy stores.

We can easily see that for E_1 to be less than E_2, we need:

$$R'\ell I_1 + L'\ell \frac{dI_1}{dt} < 0 \tag{7}$$

There is only one parameter that can be negative and that is dI/dt. As more stores are added and more stores are active at the same time, the voltage at the active store farthest from the armature becomes lower and lower due to an increasing number of negative dI/dt terms. This voltage reaches a minimum when the system reaches "steady state" (i.e., there is a constant number of active stores at any time).

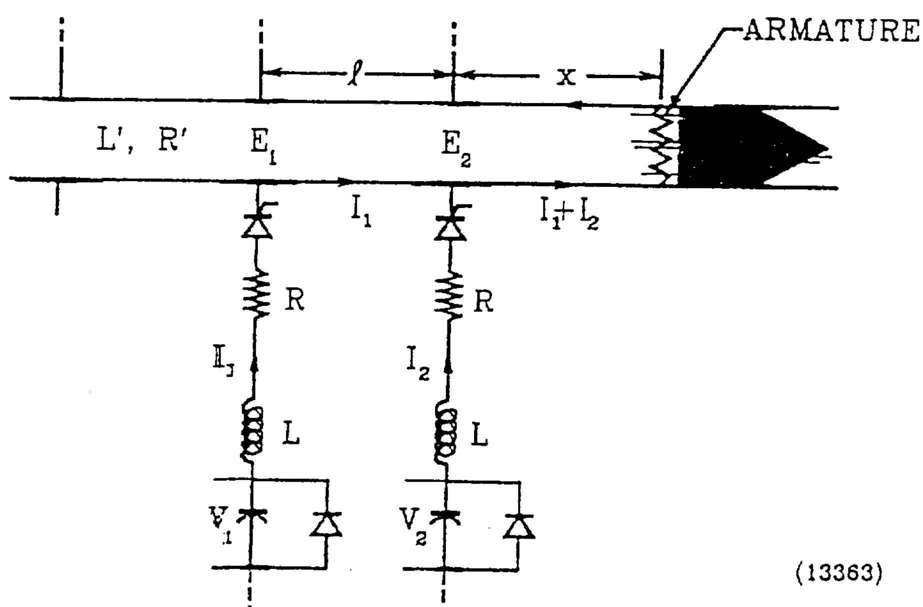

Figure 4. A two stage UDESS EM launcher.

2.3.2 UDESS Requirements for Prevention of Secondary Armatures

In order to determine if a UDESS has the capability to prevent secondaries (and thereby overcome the velocity limit) we first need to know what is required to prevent secondaries. From the above discussion, we know that we need to reduce the rail-to-rail voltage. During Phase I of this program we developed a set of requirements for the UDESS to prevent secondary formation.

The first requirement is a criteria specifying voltage level versus location behind the main armature. According to Parker,[4] the voltage gradient should be reduced to below 40 V/mm (rail-to-rail voltage/rail-to-rail spacing). This is based on observations of the rail-to-rail voltage when secondaries form. Our own observations of experimental data agree with this value. This voltage gradient means that for a 20 mm rail spacing, the voltage needs to be held below 800 V. If we scale this up for a 500 mm rail spacing, the threshold voltage increases to 20 kV.

The second requirement of how close to the armature/projectile the voltage needs to remain below. Observations indicate that distinct secondaries usually form no closer than 20 bore diameters (0.4 m for a 20 mm rail spacing) from the main armature. Therefore, we want the rail-to-rail voltage to be reduced to less than 40 V/mm at a location no farther than 20 bore dimensions from the projectile.

A third requirement is the location relative to the armature at which a power supply should be discharged in order to maximize acceleration force. We have found that the minimum resistive loss occurs in an armature that is approximately 5–10 bore diameters in length. Also we have found that current should flow in the rails for about four bore dimensions in order to get the full $\frac{1}{2}L'I^2$ driving force. This gives a maximum useful armature length of about 15 bore dimensions (or 0.3 m for a 20 mm bore) with an optimal supply firing point at 4 bore dimensions behind the main armature.

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4. Jerald V. Parker, "Why Plasma Armature Railguns Don't Work (and What Can be Done About It)," IEEE Transactions on Magnetics, Vol. 25, No. 1, Jan. 1989, pp 418-424.

SECTION 3

DEVELOPMENT OF THE UDESS ELECTROMAGNETIC LAUNCHER

Many of the design challenges for developing an electromagnetic launcher were familiar to us and easily overcome, while other challenges were new to us and presented more difficult obstacles. For example, designing and implementing the controls to fire the 32 stage power supplies at the proper times were particularly important and problematic. Another difficult problem was finding a launch package design that was both light enough to achieve our velocity objectives and durable enough to survive the launch. In this section we discuss the technical problems encountered for each design issue, the methodology used in addressing the problems, and the solutions which resolved the problems.

3.1 SYSTEM DESIGN

The first step in the development of the UDESS prototype launcher was to finalize the system design parameters. The performance parameters we were most interested in were the "Breech" voltage and system efficiency. The breech voltage represents the worst case voltage, as it is the voltage across the longest length of the launcher. If this voltage remains below our specified maximum voltage then all voltages upstream from the breech will also be below the maximum.

To determine the system design parameters we performed computer modeling for our baseline system to predict performance. This baseline system consisted of three distinct stages for accelerating the launch package. The first stage is a light gas injector which accelerates the launch package from rest up to ~450 m/s. The second stage is a breech-fed EM launcher which accelerates the launch package from 450 m/s up to 3 km/s (without secondaries). The final stage is a thirty-two stage DES-fed EM launcher which accelerates the launch package to its final velocity of >6 km/s.

We used our computer models to perform a performance tradeoff study based upon the controllable parameters in the launcher design.

The UDESS parameters which can easily be controlled are: Stage energy (by changing capacitance); Stage spacing; Stage current (by changing inductance); Stage pulse length (by changing resistance); and initial velocity ($v_{init.}$). For all cases we looked at the overall efficiency (kinetic energy added to the projectile divided by the total energy available (stage energy (SE) * number of stages (N))); and the voltages at the active stores closest and farthest from the armature. Table 2 summarizes our final system design which resulted from this analysis. Table 2 also gives the pertinent parameters for the stage power supplies.

TABLE 2. PHASE II SYSTEM PARAMETERS

MISSION PARAMETERS		
Launch Package Mass	=	7.5 g
Launch Package Size	=	19 mm
σ_{max}	=	55 MPa
v_{final}	≥	6000 m/s
Efficiency	≥	30%
SELECTED PARAMETERS		
Bore Size	=	19 mm
Bore Shape	=	Square
Launch Package L/D	=	1.5
Barrel	=	IAP Laminated Design (L′ = 0.448 μH/m)
DERIVED PARAMETERS		
Kinetic Energy	=	135 kJ (0.760 kJ + 14.240 kJ + 120 kJ)
Maximum Acceleration	=	4.0 Mm/s^2
Maximum Current	=	350 kA
Minimum Launch Time	=	0.82 ms
Minimum DES Launcher Length	=	3.7 m
STAGE PARAMETERS		
Charge Voltage	=	10 kV
Stage Energy	=	10 kJ
Stage Current	=	100 kA
Stage Spacing	=	0.25 m

The prototype UDESS launcher design used for this program required the development of six main subsystems. The subsystems are — Stage Power Supplies, Launcher, Interfaces, Discharge Controls, Launch Package, and Auxiliary Equipment. Each of these subsystems and equipment are described in greater detail in other sections of this report.

3.2 LAUNCH PACKAGE

During the course of this program both plasma armature and metal armature launch packages were developed and tested. Under the initial program plan only plasma armature testing was to be completed. As the program progressed we decided to perform additional testing with metal armature launch packages in our prototype UDESS system.

3.2.1 Plasma Armature Launch Package

The design requirements for the plasma armature launch package were:

- Maximum Mass : 8 grams
- Maximum Accelerating Force : 20 kN
- Bore Size (square bore) : 19.05 mm
- Launch Package Length (L/D = 1.5) : 28.5 mm
- Maintain Structural Integrity
- Plasma Obturation
- Plasma Armature Initiation
- Compatible with Downrange Velocity Measurement

The original maximum allowable launch package mass, in order to reach our velocity goal, was 5 grams. Due to changes to the system design as the project progressed, where the number of UDESS stages was increased from 25 to 32, the maximum permissible launch package mass was increased to 8 grams. This greater mass allowance permitted the design of a stronger launch package that maintained its integrity through to the catch tank.

Many different launch package designs were fabricated and tested before we found a material and a design that was successful. The various materials tested included aluminum, graphite, fiberglass, Lexan, and Nylatron, with most of the designs being variations of a hollow block form. The candidate designs were fabricated and statically tested in a hydraulic press to determine if they were capable of withstanding a 20 kN launch force. The designs which passed the static test were then launch tested.

The final plasma armature launch package design used was a Lexan type shown in Figure 5. Figure 5 shows the complete launch package assembly. Included in this assembly is the launch package, which has a rubber plasma obturator attached, and the pusher block, which has the fuse attached to it. The pusher block holds the fuse against the rear of the launch package and is required when using the light gas injector. We initially injected the launch package without a pusher block but experienced failures which resulted in severe damage to the launcher. With the fuse attached directly to the plasma obturator, it would occasionally become separated from the launch package. When this occurred and the launcher was triggered, the lack of a closed electrical circuit (fuse) resulted in the electricity finding the path of least resistance, typically breaking down at the BJ bank interface. The addition of the pusher block eliminated this problem but also resulted in a lowering of the launch package velocity from the injector.

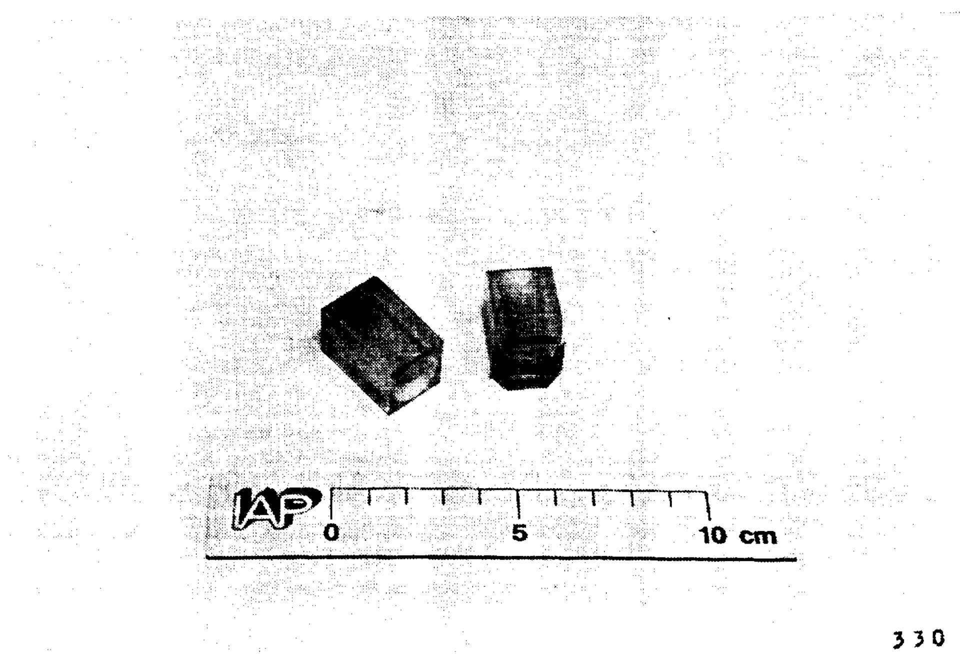

Figure 5. The plasma armature launch package.

3.2.2 Metal Launch Package

Metal launch packages were also utilized. An example armature is shown in Figure 6. This launch package has a launch mass of 41.6 grams. A second launch package type which utilized a metal armature is shown in Figure 7. This second launch package was significantly lighter, with a mass of 32 grams.

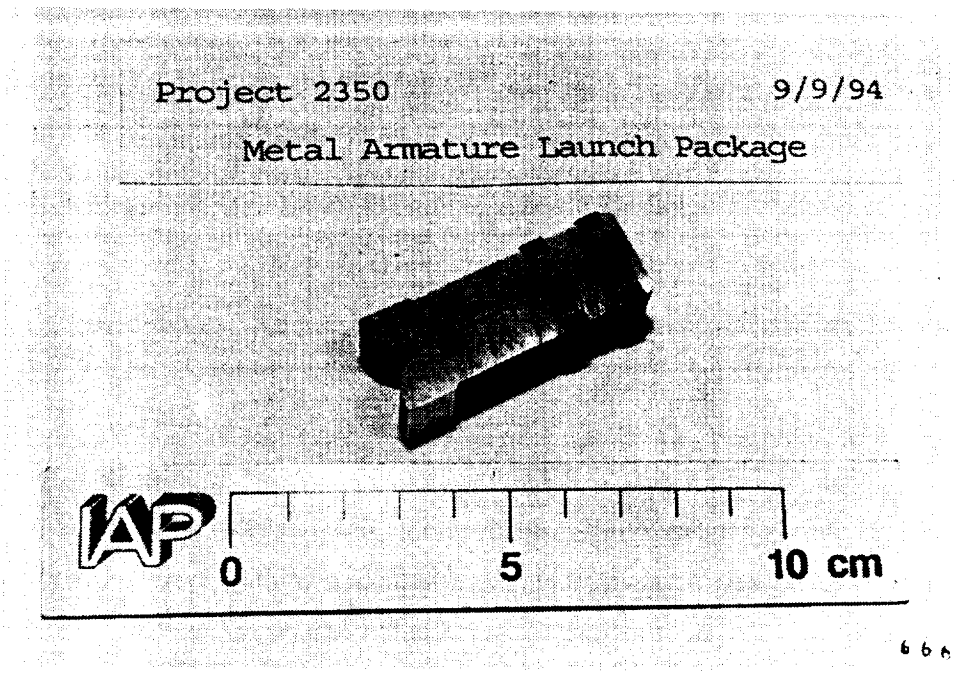

Figure 6. A metal launch package.

3.3 LAUNCHER

The launcher is comprised of three sections; a 2 meter long light gas injector, a 1 meter long breech-fed EM preaccelerator, and the DES-fed EM launcher, which can be assembled from 2 to 8 meters in length.

3.3.1 Injector

The first stage of the launcher is a gas injector. The injector requirements are a 19.05 mm x 19.05 mm bore and an exit velocity $\geq$ 450 m/s for a launch package mass $\leq$ 5 grams. For heavier

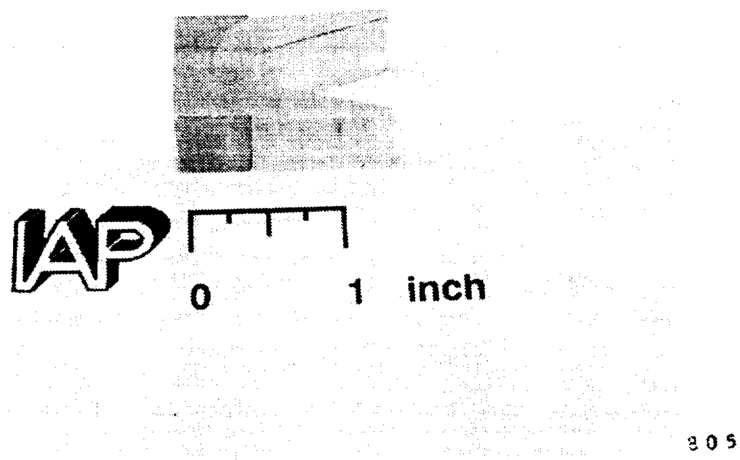

Figure 7. A lightweight metal armature launch package.

launch packages the velocity is correspondingly lower. We used our existing 2 meter gas injector which is shown in Figure 8. A new core with the 19.05 mm square bore dimensions was fabricated and installed. Test firing of the injector indicated that it would consistently provide the required exit velocity with a 8 gram launch package. Test data for both 15 and 19 mm bores is shown in Figure 9.

For metal armature launches we modified the gas injector to accept the wider metal launch package. The width of the gas injector was increased slightly using shim stock, allowing the metal armature to be accelerated without excessive drag in the injector.

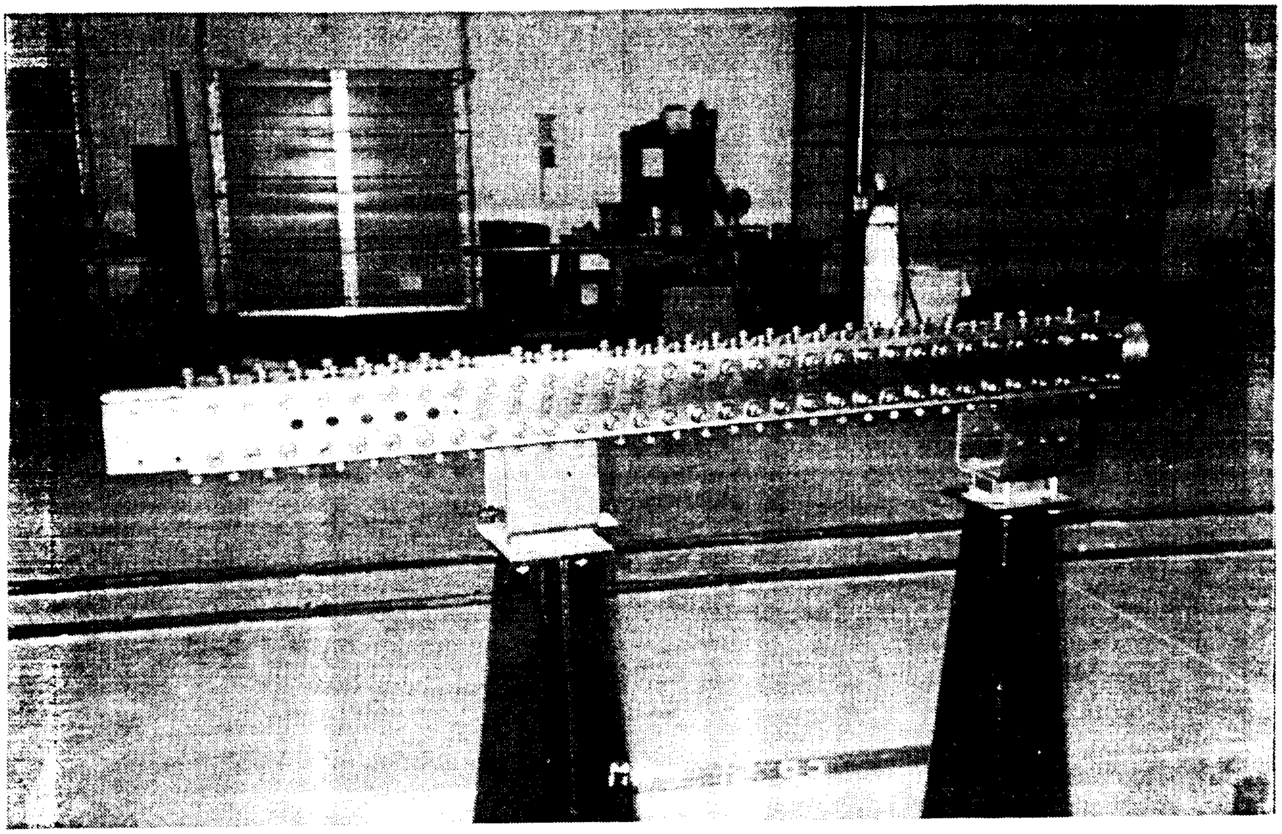

Figure 8. We used a light gas gun as an injector.

3.3.2 EM Preaccelerator

The EM Preaccelerator is 1 meter long and was breech fed by our existing BJ bank. Our BJ bank has the capability of sourcing current in excess of 1 MA into a launcher of this size. The requirements for the EM Preaccelerator were:

• Bore Size (square bore):	19.15 mm x 19.15 mm
• Exit Velocity :	3000 m/s
• Peak Current :	300 kA
• Vacuum Capability:	≤ 40 Torr
• Straightness :	≤ 1 mm/m
• Bore Size Variance:	± 0.25 mm

In order for the entire system to function properly, it was necessary for this section of the launcher to accelerate the launch package with no secondaries. The vacuum requirement exists to

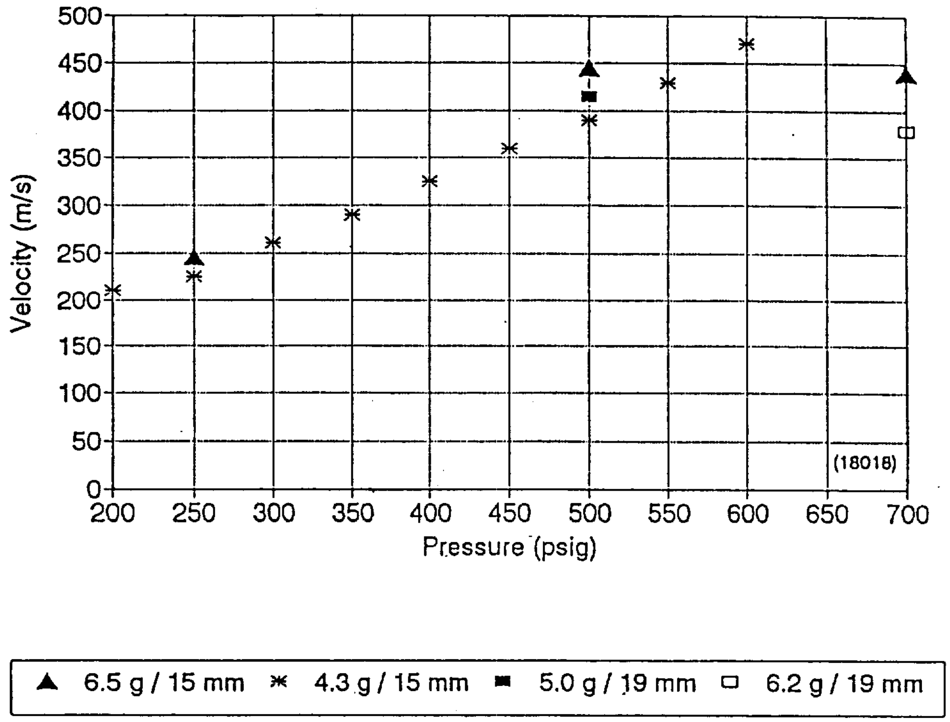

Figure 9. The injector meets our specified requirements.

eliminate the air mass in front of the launch package which would otherwise need to be accelerated. The air mass remaining at a 40 torr vacuum is approximately 0.2 grams or 2.5% of the total launch package mass. The bore straightness and size variance requirements are based on the lateral acceleration limits and plasma obturation requirements of the launch package. The requirements listed above were all conservatively selected.

The core components of the preaccelerator are shown in Figure 10. The EM preaccelerator was assembled using existing barrel containment structures and supports. Launcher sections were assembled with 6.35 mm x 19.05 mm solid copper rails and gave good vacuum sealing results. The launcher core uses stepped insulators fabricated from G-9 phenolic laminate and used in 4 ft. lengths. G-9 was selected based on published data which indicated that it produces less barrel contamination during a plasma armature shot than other materials, such as G-10 or Lexan. The stepped insulators (as opposed to stepless insulators) reduced the variations in bore dimensions and simplified the assembly procedure.

The launcher bore dimensions were repeatable to within ±0.1 mm (±0.004 inches) in both the rail-to-rail and insulator-to-insulator directions. The highest vacuum level achieved was 30 torr, however, at this vacuum level we experienced voltage breakdown at about 1 kV. A study of

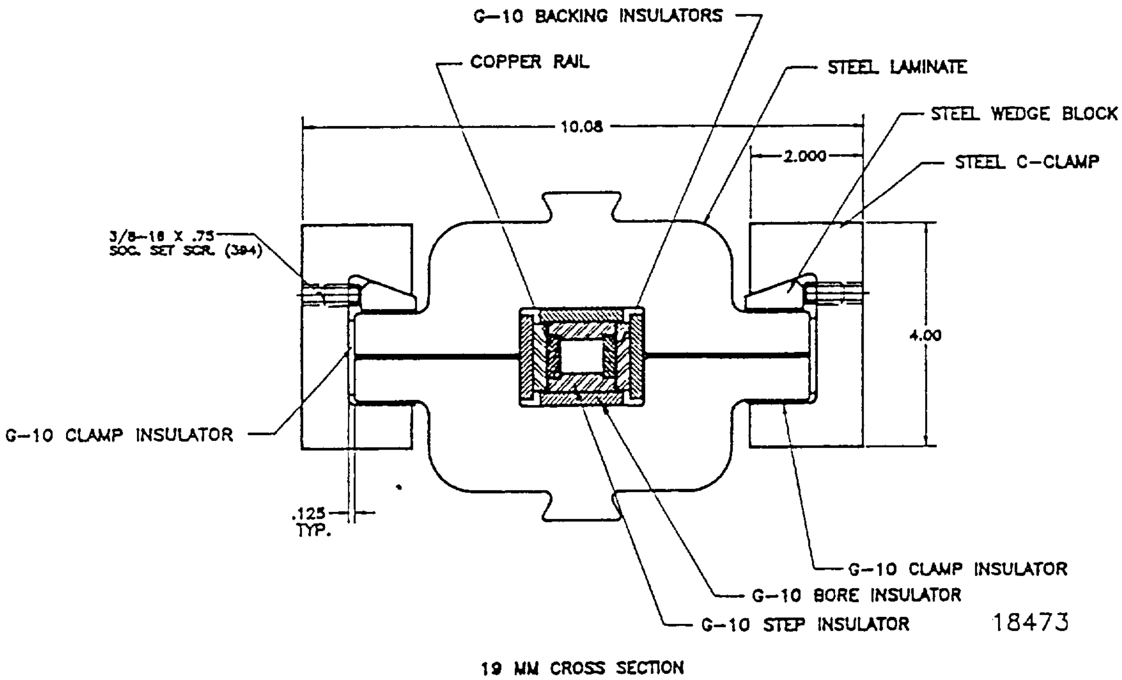

Figure 10. A cross section of the EM preaccelerator.

theoretical breakdown voltage versus vacuum level showed that at vacuums above 85% vacuum the breakdown voltage is below 4 kV. The breakdown voltages we measured were lower than this Paschen curve data, as shown in Figure 11. To increase the standoff capability to 4 kV, we decreased the vacuum level requirement to 110 torr which is an 85% vacuum. The launcher demonstrated the ability to maintain this vacuum level and voltage standoff for multiple shots.

The interface between the BJ bank and the EM Preaccelerator was made with standard copper flanges and aluminum bus plates. This interface was designed for a resistance $< 225\ \mu\Omega$ and inductance $< 1\ \mu H$. The power to the interface was carried by a custom coax conductor made with a 76 mm copper pipe outer conductor and a 350 MCM welding cable inner conductor. This interface was on several occasions severely damaged, but in all cases this was due to other problems within the launcher, as described in Section 3.2 above.

Existing trigger electronics from our BJ bank system were utilized to control the discharge of the EM preaccelerator. Included in these controls are trigger generators and timing delay generators for each of the eight modules which make up the BJ bank. To initiate the discharge we used a break wire trigger at the exit of the injector. Triggering of the bank was then delayed by a fixed amount to allow the armature to travel into the preaccelerator before discharge. The break wire/timing delay triggering

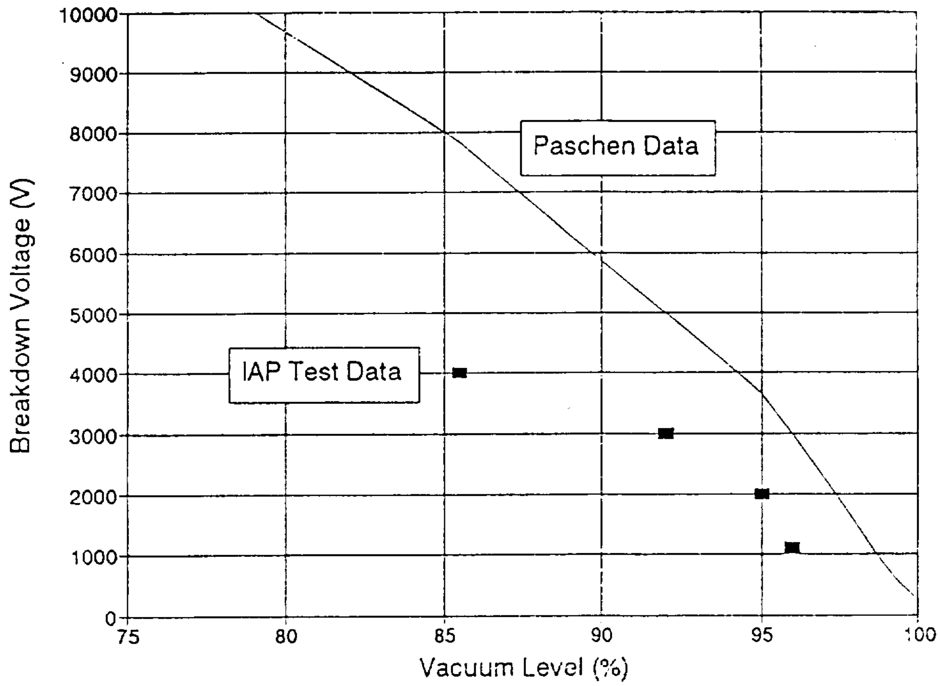

Figure 11. The launcher breakdown voltages were lower than those predicted by the Paschen curve.

for this section of the launcher was very reliable throughout this program.

3.3.3 DES-fed EM Launcher

The DES-fed EM Launcher is powered by the Distributed Energy Stores (DES) and ranged from 2 m to 8 m in length, where 2 m of barrel structure was used for every 8 stage power supplies inserted into the system. The core components of the DES-fed EM launcher section are shown in Figure 12. As can be seen in Figure 12, the launcher cross section is the same as the EM preaccelerator, only with the addition of the DES feeds. The DES launcher was subject to the same design requirements as the preaccelerator with the addition of the stage power supply feed requirements. These feeds were rated for a current of 100 kA and a breakdown voltage in excess of 3 kV.

The feeds were made from aluminum. Contact pressure with the rail is provided by the E/M rail repulsion force. This concept was tested by firing DES stage power supplies incorporated into the 1 meter preaccelerator. The DES feeds were sized such that their thickness was 0.025 mm to 0.05 mm thicker than the adjacent insulators. This ensured that the feeds were forced into contact with the rails. This additional thickness showed up as a slight reduction in bore dimension at the eight feed

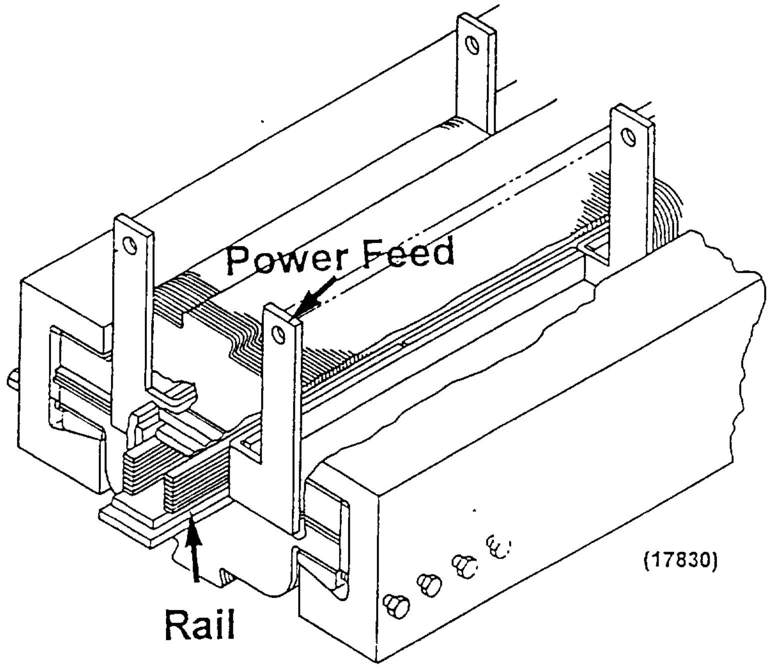

Figure 12. A section of the DES-fed EM launcher.

locations, starting at about 0.2 m from the muzzle and spaced about every 0.25 m. Bore measurements indicated that there were no detrimental effects on bore dimension due to the DES feeds.

During initial testing of the DES section of the launcher it was discovered that the feeds were arcing to the rails, causing unwanted current conduction between the feeds and rails along the length of the feed. The original design was based on a quarter meter long feed with a small area exposed for contact and the rest anodized for insulation. This was done to simplify assembly of the launcher and to allow us the flexibility to change the contact location if desired. This problem was solved by simply shortening the length of the DES feeds to only the contact area and filling the vacated space with a separate insulator.

3.4 INTERFACES

There are three interfaces in the launcher. They are; the Injector to Preaccelerator interface, the EM Preaccelerator to DES Barrel interface, and the DES Barrel to Flight Tube interface. The requirements for these interfaces were:

- Maintain bore alignment to within ± 0.05 mm
- Maintain a bore straightness of ≤ 5 mm/m
- Provide electrical insulation in excess of 3 kV
- Maintain vacuum diaphragm sealing to ≤ 40 Torr

3.4.1 Injector-to-Preaccelerator Interface

Photos of the completed interface are shown in Figures 13 and 14. The interface was made from G-10 fiberglass material. A Mylar diaphragm was used for vacuum sealing and was placed between the two G-10 pieces shown in Figure 14. Guide pins and bushings aligned the pieces while the latches shown provided the force necessary to seal the diaphragm. This provided a consistent interface that is easy to assemble with simple replacement of diaphragms when needed. The interface was designed for both plasma armature and metal armature launches. The EM launcher breech interface is tapered, which preloads the metal launch package contacts by the desired amount prior to the application of current.

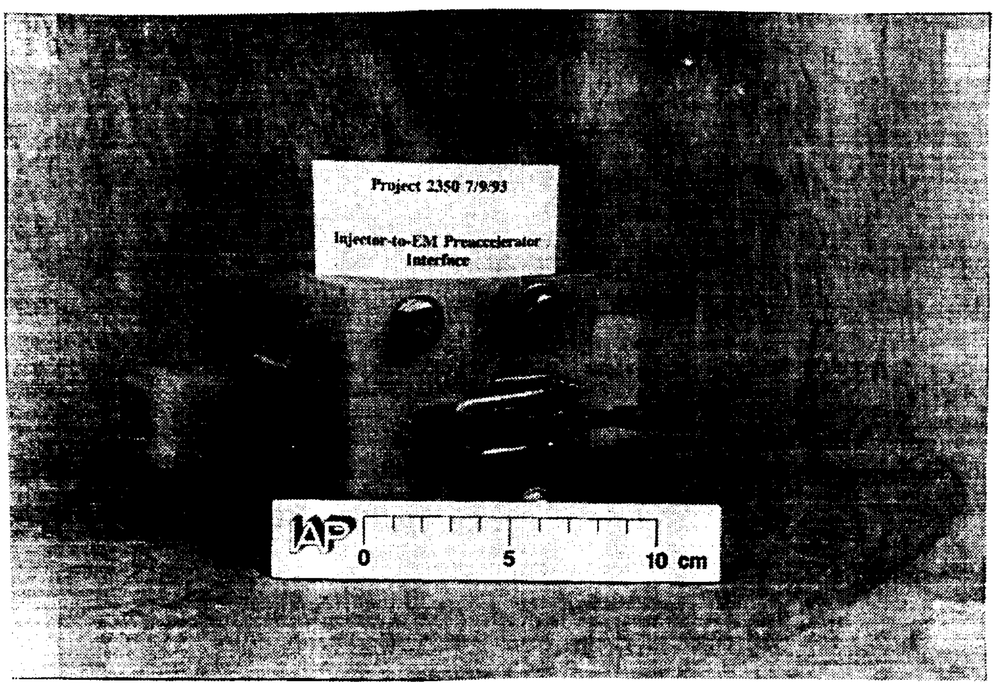

Figure 13. The injector to EM preaccelerator interface.

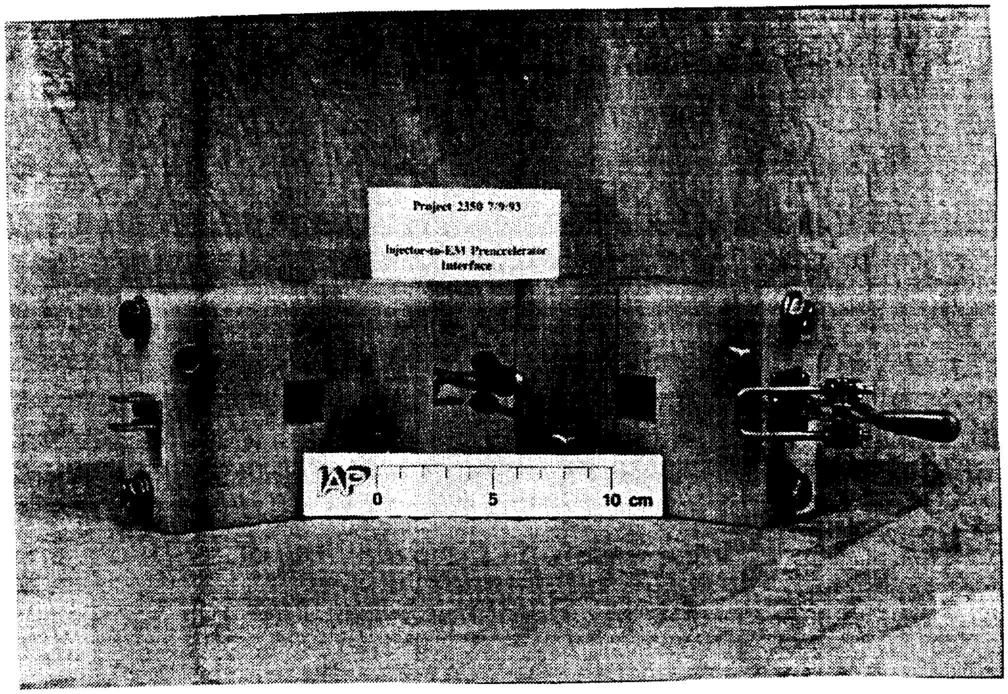

Figure 14. The interface is a split design which can accommodate a vacuum diaphragm.

3.4.2 EM Preaccelerator to DES Barrel Interface

The interface between the preaccelerator and DES barrel is transparent, where the two EM launchers are assembled from identical components. The primary issue in designing the interface between launchers was the fabrication of a continuous set of rails between the two sections. The rail material is only available in 12 foot lengths, therefore a rail joining technique was required. Several methods of joining the rail sections were tested including Silver Soldering, Welding (with various post-weld treatments), and Bronze Brazing. Each sample was tested for hardness in and around the joint area. Welding was the rail joining method which was selected and tested in the launcher. We experienced no difficulties with the welded joints during the course of this program.

3.4.3 DES Barrel to Flight Tube Interface

The launcher to range flight tube interface is shown in Figures 15 and 16. This interface includes provisions for a shorting block which is also used to form an arc horn at the muzzle. The interface was also designed to accept probes for measuring muzzle voltage.

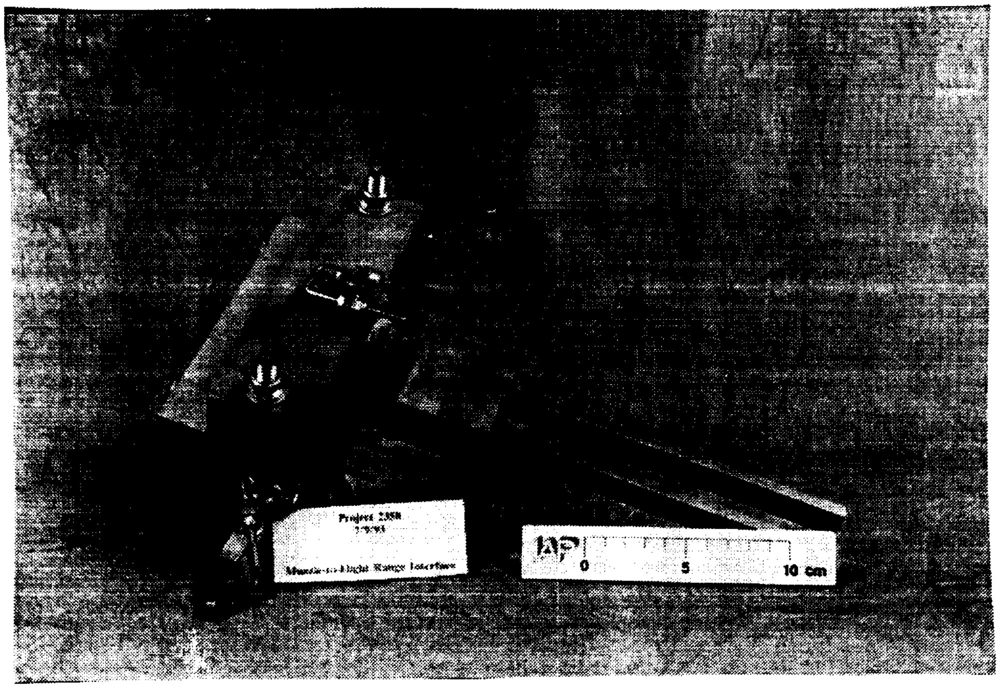

Figure 15. **The DES launcher to range flight tube interface.**

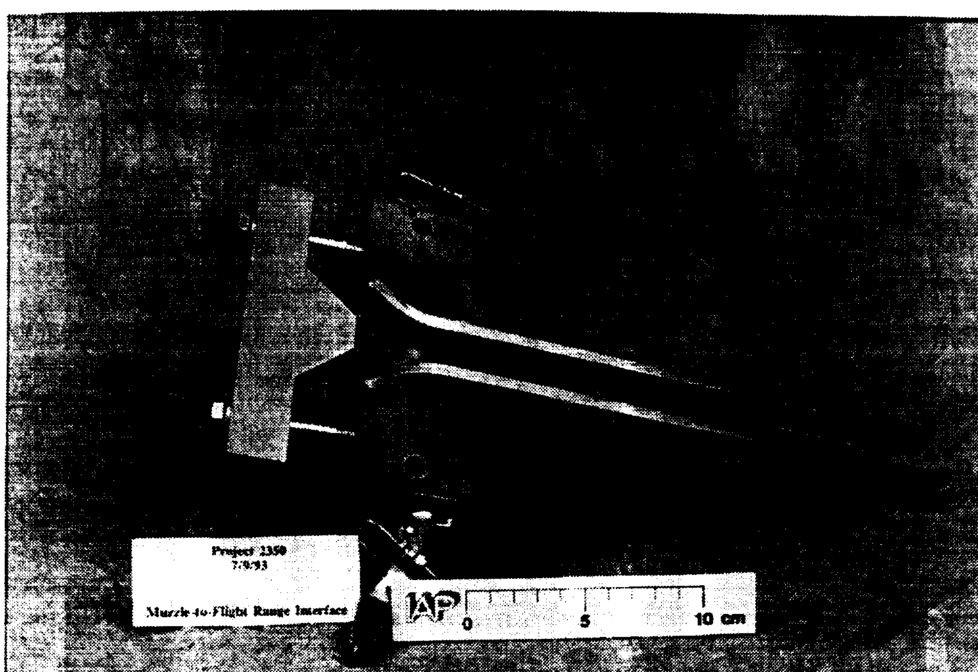

Figure 16. **The interface incorporates a shorting block.**

3.5 STAGE POWER SUPPLIES

The stage power supplies consist of two main subsystems: the charging system, with safety dumping capability, and the primary discharge system. These subsystems are described in detail below.

3.5.1 Charging System

The charging controls consist of a high voltage power supply, isolation switches, balance resistors, and a dump resistor. The stage supplies were built in 4 racks of 8 stages each. A simplified schematic for the charging system is shown in Figure 17. Charging of the stage supplies is accomplished using an existing 10 kV, 100 mA supply. This supply was capable of charging all of the stage supplies in under 10 minutes. The HV supply had a single safety discharge switch and dump resistor already installed.

Each of the four power supply banks and a 2 pole, 8 position isolation switch which disconnected the charging supply (both the high voltage and the ground lines) from the supplies and at the same time disconnected the stage power supplies from each other. This disconnect switch was air actuated and controlled by a solenoid operated valve. A balance resistor was located in series with each stage supply energy storage capacitor. The resistors are liquid filled ($CuSO_4$ in water) and provide isolation between stage supplies during safing. If one or more of the stage supplies did not fire during a shot, these resistors limited the current flow between supplies when the disconnect switch was reengaged prior to dumping the charge from the banks. The balance resistors were sized to dissipate 10 kJ of energy, the maximum amount that any one stage stored. To complete the safety discharge of the system, the dump relay in the high voltage supply was enabled. The stored energy was then dissipated in both the balance resistors and the dump resistor incorporated into the high voltage supply.

3.5.2 Discharge System

A schematic for the stage power supply is shown in Figure 18. Each stage power supply was a simple capacitive/inductive energy store. The requirements for the individual components within the supply are listed in Table 3. The crowbar diodes and reverse current blocking diode, along with the necessary buswork to connect them to the capacitor and ignitron, were ordered as a single assembly.

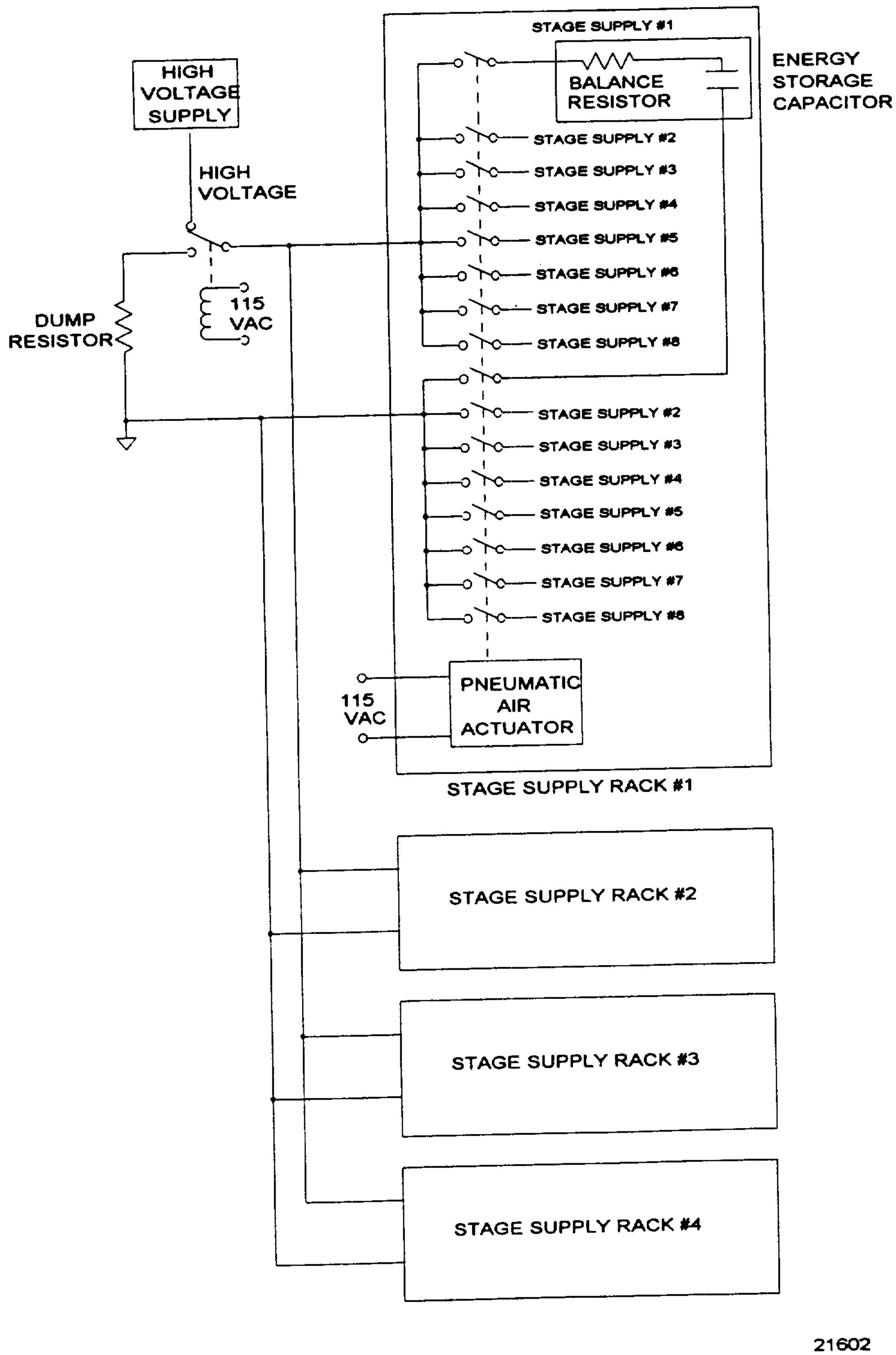

Figure 17. A simplified diagram of the charging system.

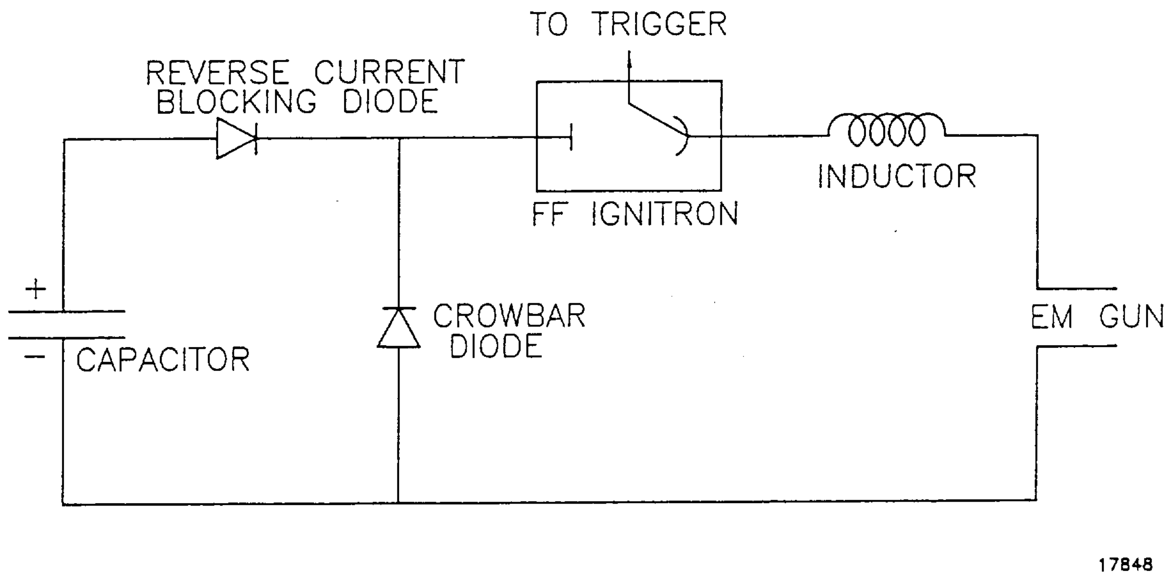

Figure 18. **The stage power supply is a simple capacitor/inductor energy store.**

TABLE 3. STAGE POWER SUPPLY COMPONENT REQUIREMENTS AND SELECTIONS

COMPONENT	OPERATING RATINGS	COMPONENT RATING
Energy Storage Capacitor	10 kV, 10 kJ, 200 µF	Maxwell - 206 µF, 22 kV
Crowbar Diode(s)	10 kV, 100 kA, 1100 kA^2s	Marconi Custom Assembly (2 – 10 kV, 50 mm dia.)
Reverse Current Blocking Diode	< 5 kV, 100 kA, 200 kA^2s	Marconi Custom Assembly (1 – 10 kV, 50 mm dia.)
Feed Forward Ignitron	10 kV, 100 kA, < 10 kA/µs, < 18 Coulomb	National - 25 kV, 300 kA peak
Energy Storage and Pulse Shaping Inductor	2 µH, 100 kA, < 500 µΩ	IAP Custom Solenoid 2 µH, 140 kA peak

Thirty-two stage power supplies were constructed in the configuration shown in Figure 19. The stage power supplies are supported by steel stands and connect to the DES power feeds via coaxial cables as shown in Figure 20. When fully assembled, they are lined up in a compact space as shown in Figure 21.

The discharge of energy from the power supplies worked as designed. Time to the current peak was 28 μsec and the decay time constant (into a short) was ~ 400 μsec. Throughout the course of this program the stage power supplies proved to be very reliable, with no failures of any components. This can be directly attributed to the conservative levels at which the supplies were operated, well below the maximum ratings for the components, as seen in Table 3.

3.6 DES DISCHARGE CONTROLS

Development of reliable discharge controls for the DES portion of the launcher proved to be the greatest challenge that we encountered during the course of this program. An electromagnetic launcher is a very hostile environment for any electronics, where careful design consideration is required. An EM launcher combines high voltages, high currents, and very rapid energy transfer to produce an environment that can interfere with the operation of, and potentially destroy, electronic circuitry. The discharge controls required isolation from voltages to 20 kV and currents up to 350 kA. The voltage potentials and currents within the launcher are rapidly changing, requiring a controls design that minimized capacitive and inductive noise coupling.

A top level block diagram of the discharge controls is shown in Figure 22. The control system was of a modular design which allowed for maximum flexibility during testing, allowing any subset of the full 32 stages to be tested. This architecture also allowed the controls and diagnostics modules to be easily modified or repaired.

Figure 23 illustrates the functionality incorporated into the discharge controls. To determine the position of the armature during a launch, we monitored the change in magnetic flux density, or B-dot, within the launcher. The amount of magnetic flux within a railgun is directly related to the armature position. In front of the armature there is little flux while behind the armature there is a very high level of flux. We placed a B-dot sensor across each set of UDESS feeds and used its signal to control the firing of the supply connected to those feeds. The B-dot sensors were custom cards designed and

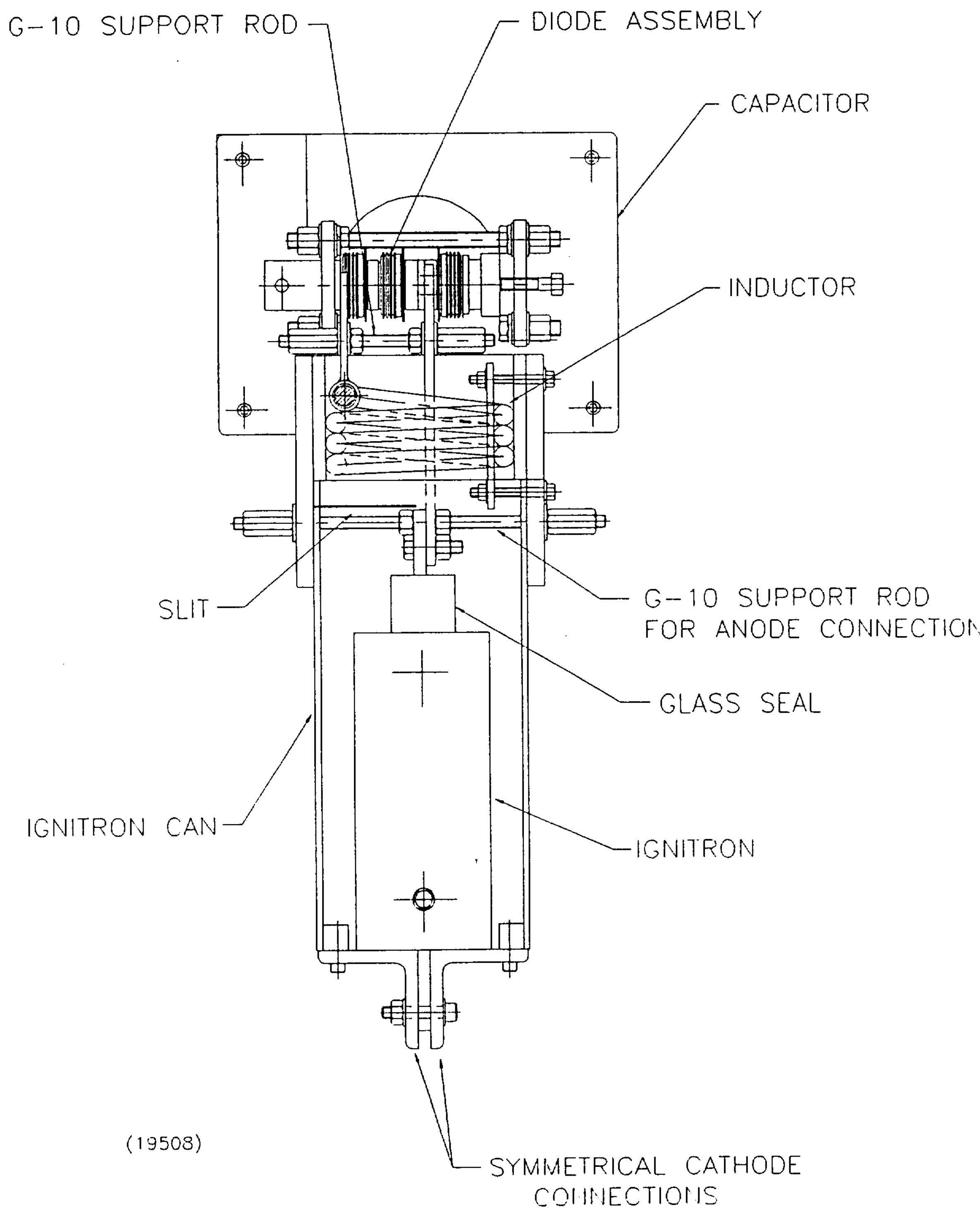

Figure 19. **The stage power supply layout design.**

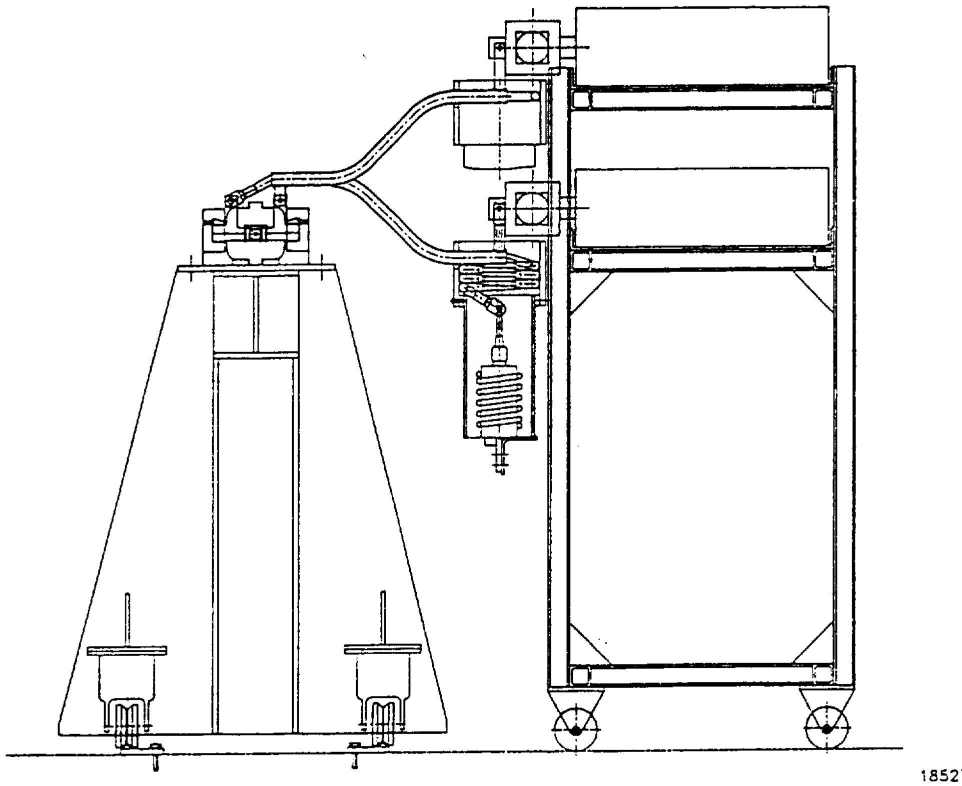

Figure 20. The stage power supplies connect to the DES launcher via coaxial cables.

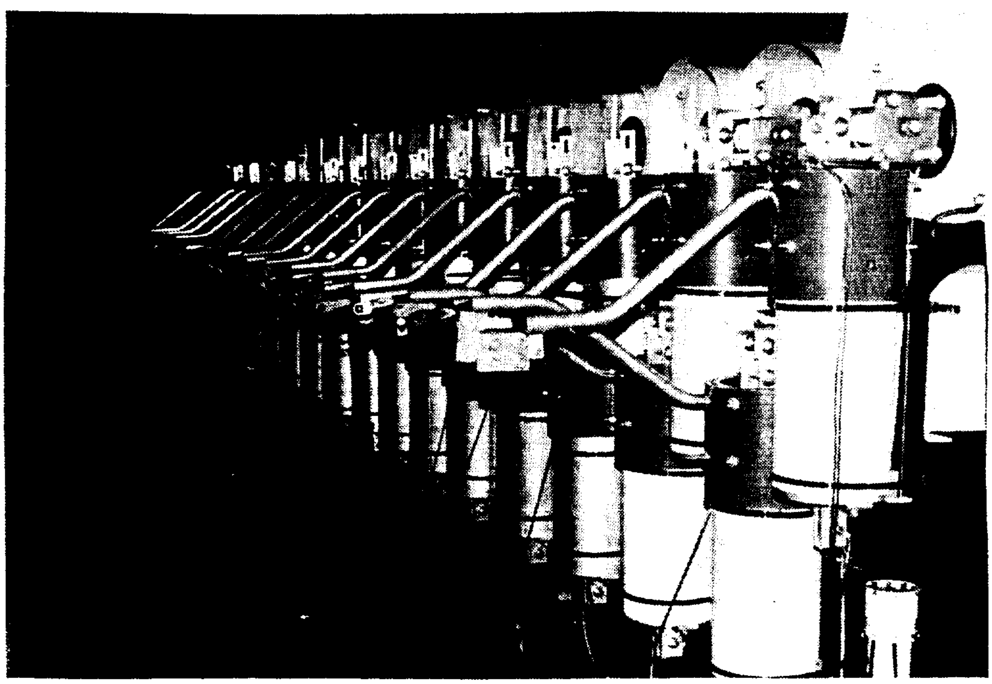

Figure 21. The completed 32 stage power supplies form a compact assembly.

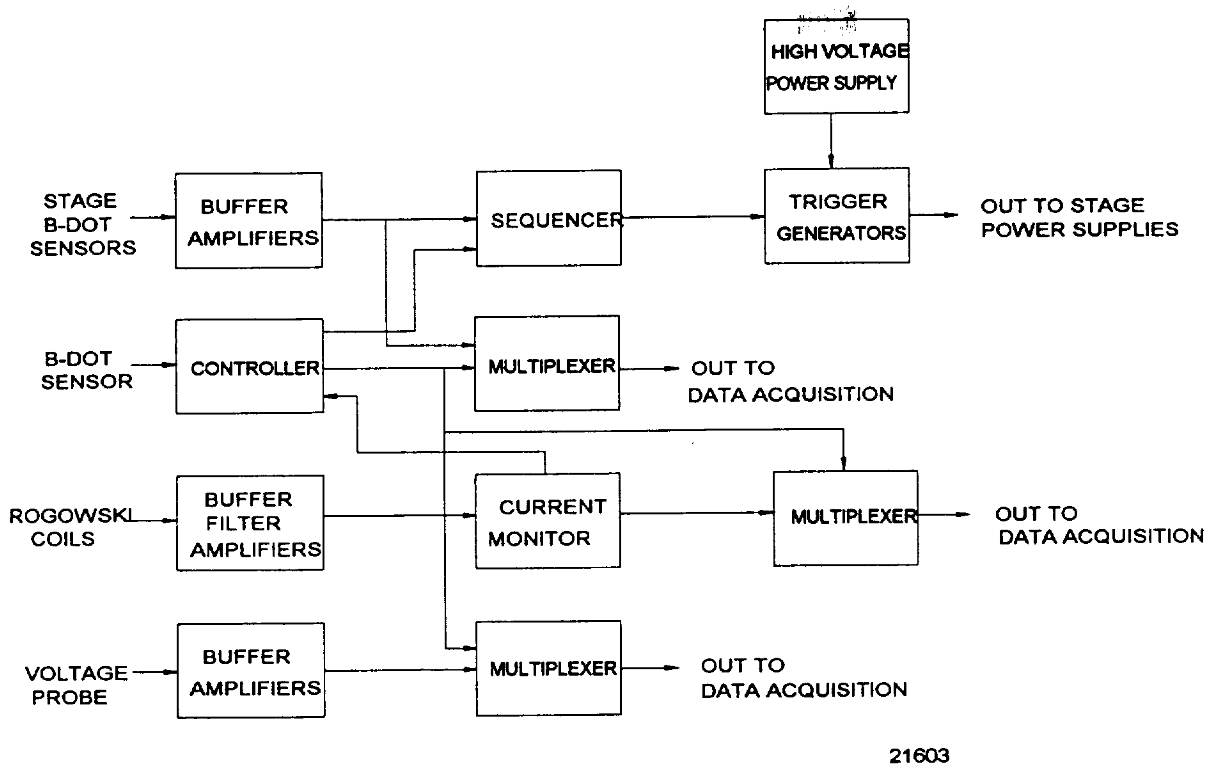

Figure 22. **Block diagram of the discharge controls.**

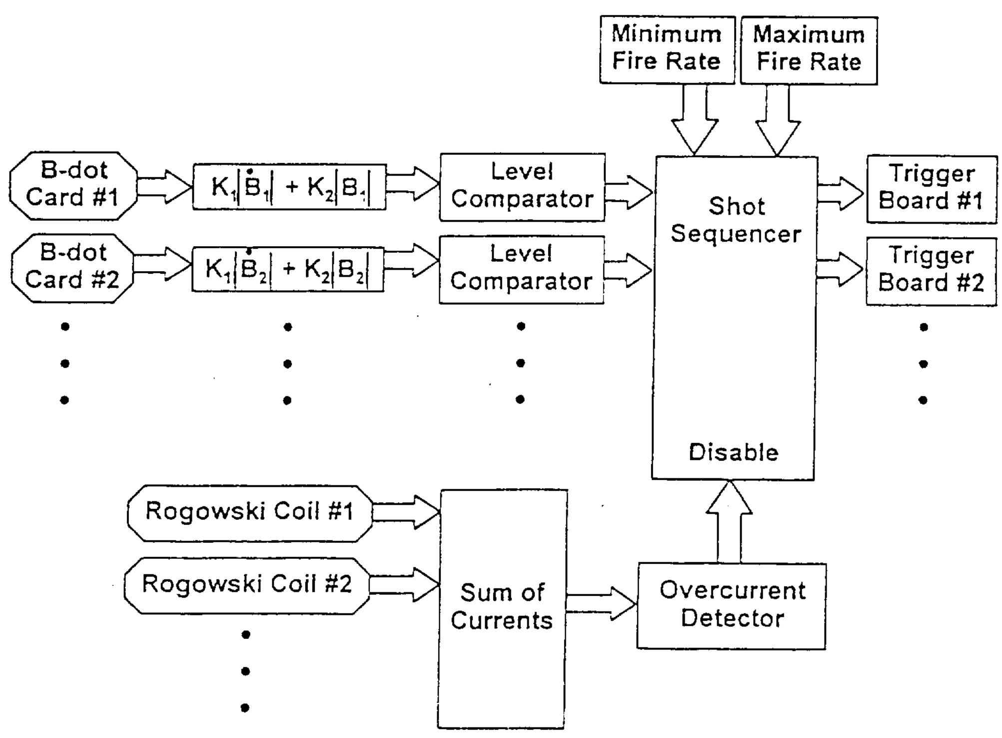

Figure 23. **A functional block diagram for the discharge controls.**

fabricated by IAP. Two of the B-dot cards are shown in Figure 24. An example the B-dot signals recorded at six positions during a railgun shot are shown in Figure 25.

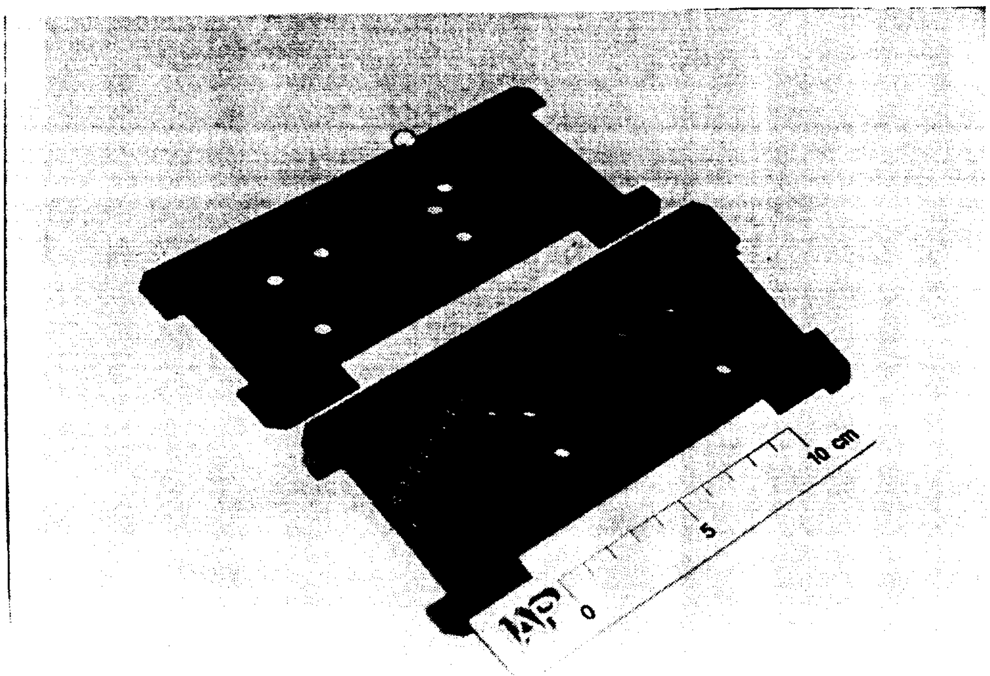

Figure 24. B-dot cards are used to measure the position of the launch package.

To determine the presence of an armature, first each B-dot signal was sent to a pair of circuits. The first circuit simply amplified the signal while the second circuit integrated and amplified the signal, the integrated signal being a measure of the barrel flux. The two signals were then recombined, where they could be adjusted for any ratio of the two signals. This summed signal was then sent to a threshold level sensing circuit which was set to recognize the change in signal level for an armature passing a B-dot sensor. Upon recognition of the armature, the next step was to compare the timing of the armature with a predetermined set of firing window values.

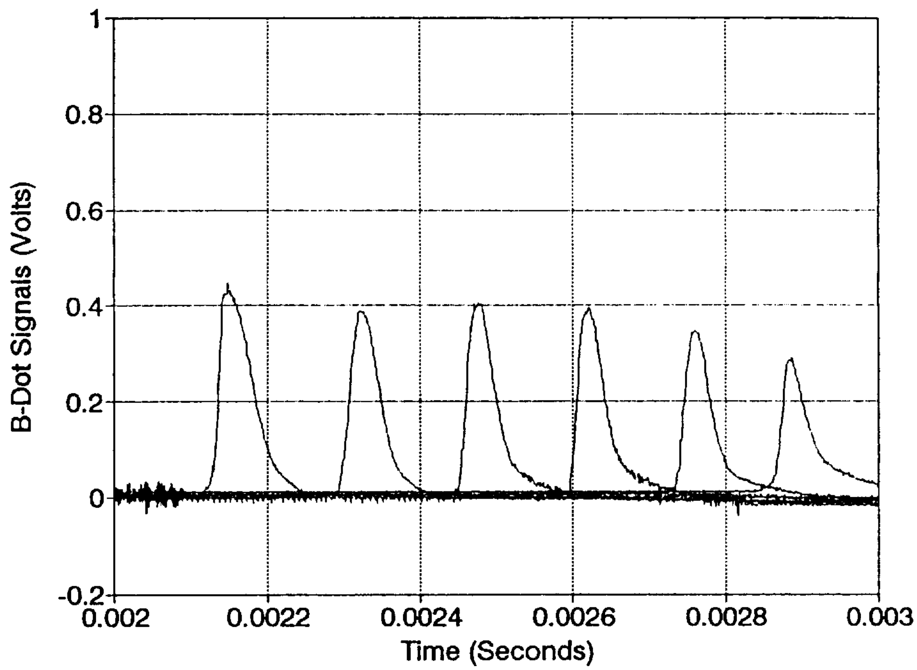

Figure 25. An example of a B-dot signal used to determine armature position within the launcher.

Each stage had a set of unique firing window times which define the minimum and maximum allowable firing times for that stage. The firing window times were calculated based upon an acceptable range of acceleration profiles for the launch package being tested. The minimum firing times represent the maximum allowable acceleration profile based upon maintaining launch package integrity. The maximum firing times represent the minimum allowable acceleration profile based upon velocity requirements.

If the armature was sensed before the minimum firing time, the stage supply was fired as soon as the timing window opened. This condition occurs when the armature is moving faster than anticipated. By triggering on the minimum time, the stage supplies "catch up" to the armature. When the armature was sensed in the middle of the firing window, the desired response, the stage supply was fired at the time of armature sense. Immediately after a stage fired the next stage down the launcher was enabled. If the maximum recognition time for a stage was exceeded, the trigger for that stage was disabled and the next stage supply down the line was enabled. This condition occurs when the armature is moving very slowly, where the supplies are not fired until the armature can catch up to the preset timing. Below is a brief description of the hardware used to implement this discharge control scheme.

3.6.1 *Signal Conditioning/Buffer Subrack*

There were a total of 96 control and diagnostic signals coming from the stage power supplies (32 currents, 32 voltages, and 32 B-dot signals). To simplify the routing of these signals and to improve upon signal fidelity they were first sent to a patch panel and signal conditioning/buffering subrack. Each signal was filtered then buffered through a differential amplifier, eliminating common mode noise which may have coupled into the cables that connect the launcher to the control electronics. A photo of the patch panel with several buffer amplifier cards attached is shown in Figure 26.

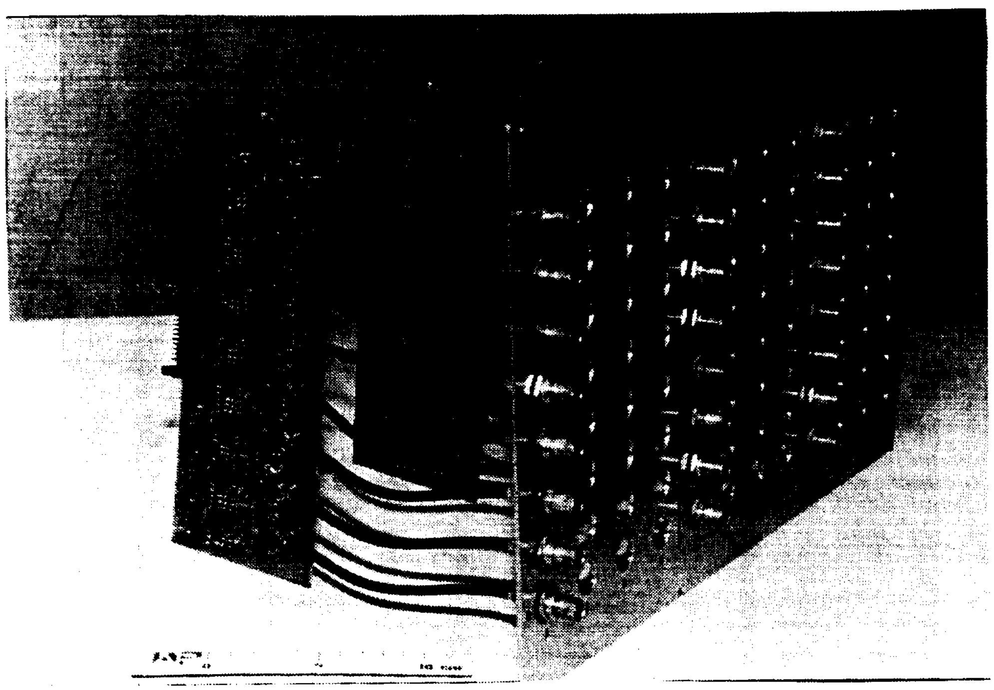

Figure 26. Signal patch panel with buffer amplifier cards shown.

3.6.2 *Stage Supply Sequencer*

The key component for controlling the UDESS launcher was the stage supply sequencer. There are a total of four sequencers required for the full 32 stage launcher. Each stage sequencer module contains all signal conditioning and timing circuitry required to sequentially trigger eight stage power supplies. The stage sequencer modules were designed to be daisy chained for sequencing as many channels as required. The sequencers were also designed to act as stand alone controllers or to be slaved to a master controller.

A photo of the sequencer is shown in Figure 27. This sequencer consists of an analog card, a digital card, and a front panel. The analog card conditioned the B-dot signals received from the barrel stages and contained the armature recognition circuitry. The digital card performed the timing comparison of these armature signals, comparing the sensed signal times to the firing window times set on the front panel. Also included on the front panel were potentiometers for each of the eight channels to control the B-dot and B (integral B-dot) summing ratio and for trigger level adjustments.

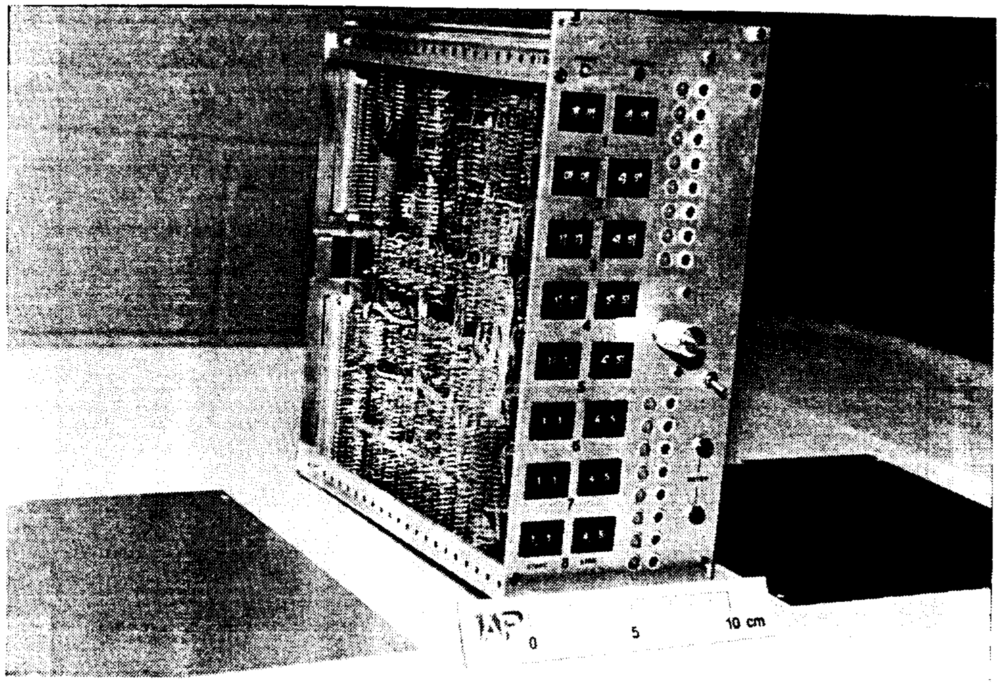

Figure 27. One of the four UDESS stage supply sequencers.

The armature recognition circuitry was very problematic and remained so right up to the end of this program. Isolation to the very high noise levels encountered during an EM launch caused many problems. In spite of the presence of filtering and de-glitching circuitry, attempts to use B-dot as the triggering signal failed. The integrated B-dot signal was far more reliable due to its high level of noise immunity, however it too had its share of problems. We occasionally experienced a very large noise "event" at the beginning of the launch when our BJ supply was fired and the plasma armature was first fused. This event sometimes manifested itself as a large negative going glitch which, when integrated, would place a negative offset voltage on the armature recognition signal. To make matters worse, these events only occurred during an actual launch, not during shorting tests or laboratory tests, and occurred intermittently.

3.6.3 *Sequence Controller*

The sequence controller was designed to initiate the UDESS portion of the launch and monitor the progress of the stage supply sequencing. A photo of the sequence controller is shown in Figure 28 below. The sequence controller contains the signal conditioning and timing circuitry required to initiate the firing sequence, the circuitry being almost identical to that described for the stage supply sequencer above. During this program, the sequence controller was very reliable at initiating the UDESS sequence of the launch. It also monitored the condition of the stages as they fired and contained error circuitry which inhibited stage firing upon detection of a fault condition. As the launch and stage firing progressed, the sequence controller also controlled data multiplexing hardware, described in Section 4 below.

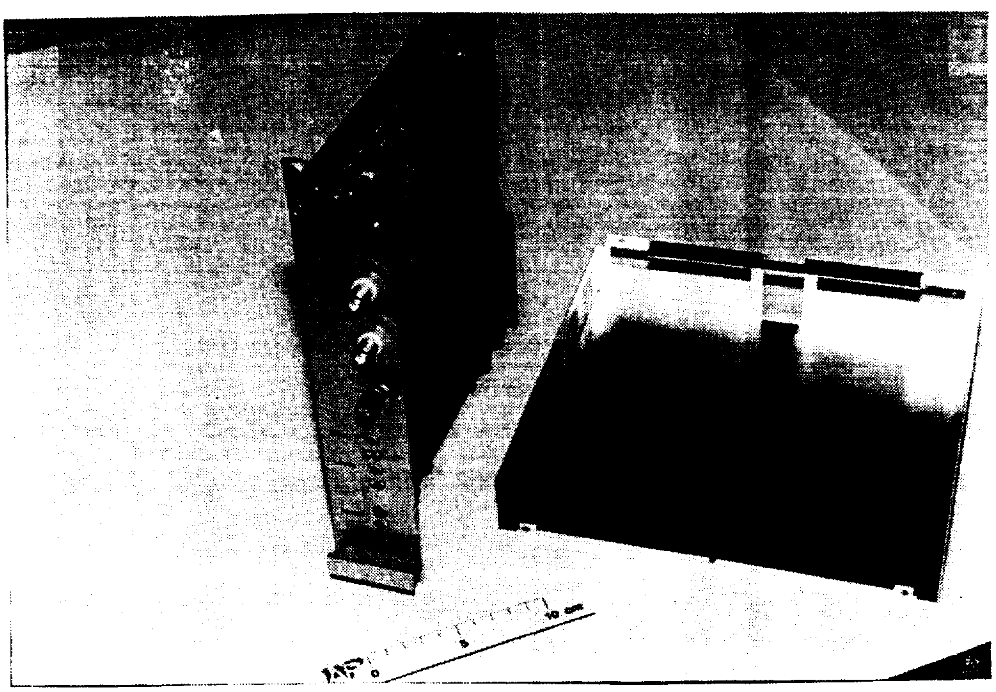

Figure 28. The sequence controller.

For this program, the sequence controller had very simple control functions. It was used to daisy chain the sequencers and to provide the master timing for their operation. However, the discharge controls have been designed such that the sequence controller can act as a master controller over the stage supply sequencers.

3.6.4 Ignitron Triggers

Triggers from the stage supply sequencers were routed to individual ignitron trigger modules for firing the ignitrons within the stage supplies. A photo of one of the ignitron trigger modules is shown in Figure 29. These trigger modules provided the ignitron with a six microsecond, half sine pulse with a peak current of 120 amps and a peak voltage of 1500 volts. The output isolation transformer within the module could hold off 20 kilovolts maximum. The ignitron triggers could be disabled by a switch on each module or by external control from the sequence controller. Also, a trigger reset, required before being fired, was performed either by a reset switch on each module or through an external control from the sequence controller. The ignitron triggers were very reliable at triggering the ignitrons during this program.

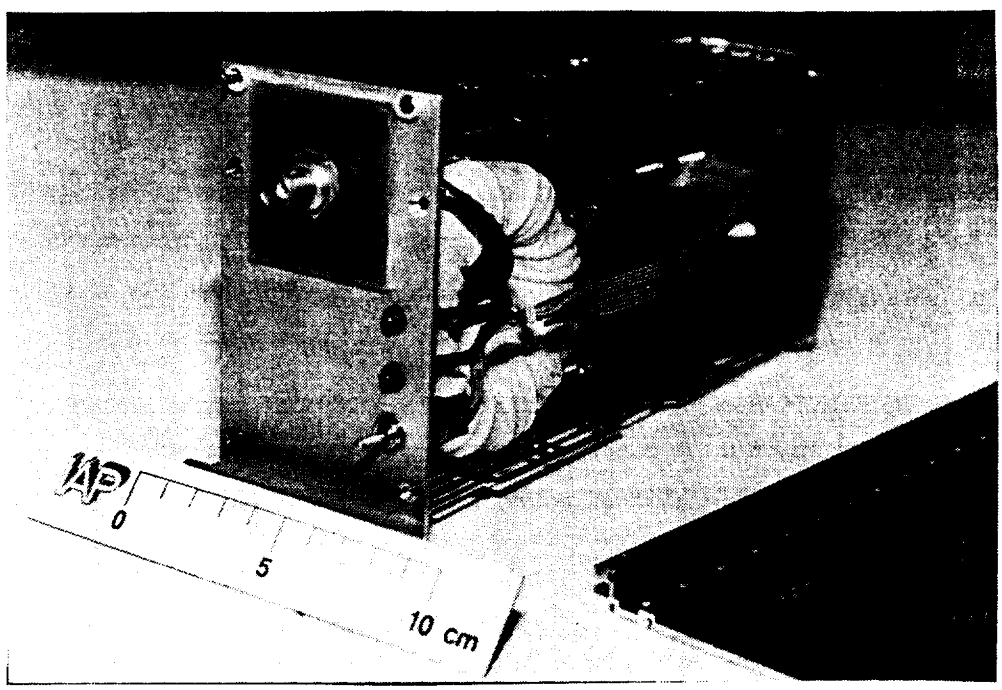

Figure 29. An ignitron trigger module.

3.6.5 Current Monitor

If the 32 stages were to fire simultaneously, the entire system would be severely damaged due to the high level of total current in the launcher. The discharge controls were designed for the implementation of a current monitoring module which was capable of disabling the system in the event that excessive current in the launcher was detected. The total current in the launcher and the individual currents from each stage were monitored. The sequence controller had the ability to disable the UDESS portion of the launcher when an overcurrent condition was detected.

3.6.6 Integration of the Discharge Controls

The discharge control subsystems described above were integrated into a single enclosure, shown in Figure 30. The enclosure contained the subracks and power supply systems required by these subsystems, and provided a protected environment, with electrical shielding, for these sensitive electronics. Included in this cabinet was a high voltage power supply for the ignitron trigger modules. This supply was designed for high isolation between triggers to avoid unwanted triggering. A high level of energy was stored in this supply so that it was very "stiff", eliminating unwanted noise signals when any stage was triggered. Included in this supply was a safety dump which allowed the rapid discharge of the stored energy when the system was not in use.

During the course of this program we experienced problems with the integration of the discharge controls. Ideally, the discharge controls would have been electrically isolated, where the system would be allowed to "float" with respect to ground. Due to cost constraints, we were unable to implement a fully floating system. To implement this system would require that all input and outputs be fully isolated up to the specified maximum level of 20 kV. We did implement this level of isolation for all input and output signal lines between the launcher and controls. But we did not isolate the discharge controls from our data acquisition system. Instead, we built a system with a very stiff, single point ground.

Due to rapidly changing energy levels, high voltages, and high currents occurring during an EM launch, it was quite difficult to maintain a good ground potential. We occasionally experienced breakdowns between the launcher and earth ground. When these events occurred we saw very high transient ground currents and voltages. These transient signals would couple into the control electronics through capacitive and inductive means, resulting in errors in operation, and on occasion causing damage to the control electronics.

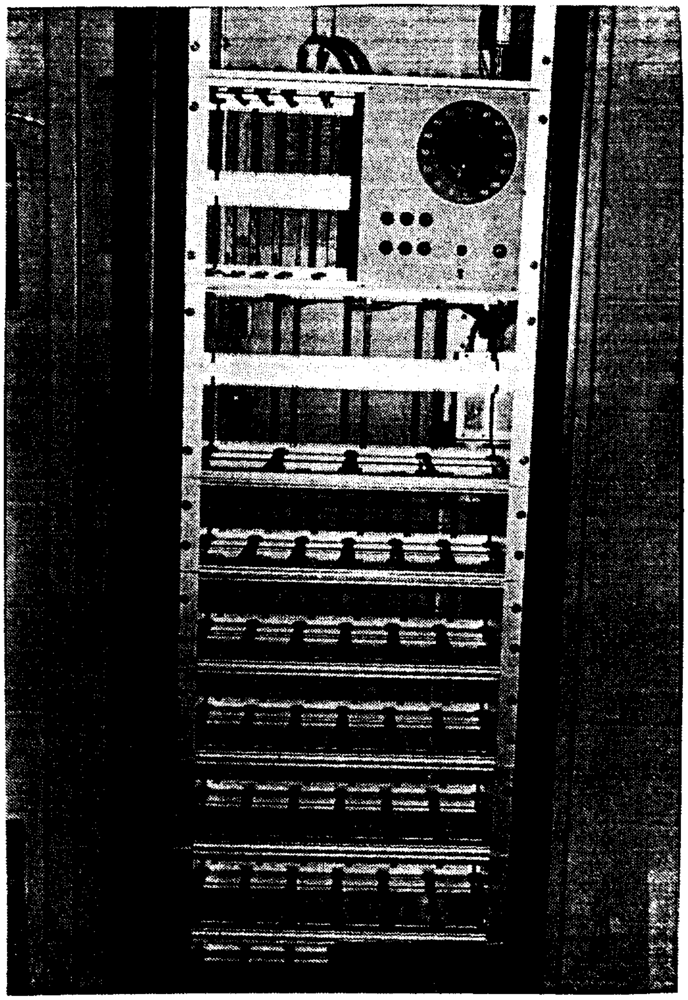

Figure 30. The discharge controls were integrated into a single enclosure.

3.7 AUXILIARY EQUIPMENT

The auxiliary equipment required to complete a UDESS launch included the vacuum system and the flight range. The vacuum system tests achieved a vacuum level of 30 torr, well below our 40 torr requirement. We constructed a flight range that was specifically tailored to the UDESS launch requirements. This range was small in volume in order to minimize the time required to pull a vacuum in preparation for a launch. The range, shown in Figure 31, included two position sensors used to measure down-range launch package velocity. The range was terminated with a catch tank for recovering the launch packages.

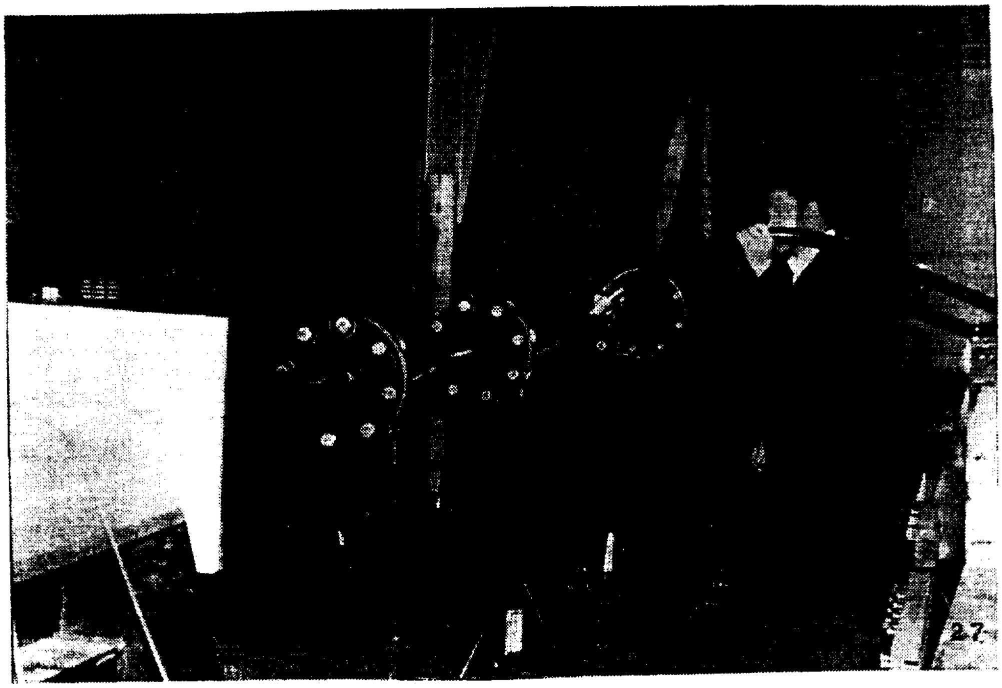

Figure 31. The UDESS flight range.

SECTION 4

UDESS PROTOTYPE LAUNCHER PERFORMANCE TESTS

We developed hardware and procedures to measure the performance of the prototype UDESS electromagnetic launcher. Due to the complexity of this system and the high volume of data required to accurately characterize the system, we developed specialized diagnostics and data acquisition equipment for test support. In this section, we describe our test hardware and present a summary of the tests which were performed on the UDESS launcher and subsystems.

4.1 DIAGNOSTICS HARDWARE

For this program, we developed specialized diagnostics hardware to measure important parameters within the EM launcher. This hardware was evolved from existing designs which we have successfully utilized during previous EM launcher development programs.

4.1.1 Current Sensors

To monitor current in the UDESS launcher we utilized Rogowski coils. These coils are used extensively in pulsed power applications and are well characterized. One of the Rogowski coils is shown in Figure 32. These coils were custom fabricated and calibrated at IAP. These coils are very flexible and were wrapped around the conductor for which the current was to be measured. The signal from a Rogowski coil is a voltage which is proportional to the change in current with respect to time (dI/dt). To determine the current within the conductor the output signal is therefore integrated. We perform this integration using a non-ideal integrator (low pass filter) in combination with digital error correction in post processing. This non-contact method of current measurement provides very good accuracy while maintaining a high level of isolation.

4.1.2 Voltage Sensors

To measure voltages in the launcher we utilized the combination of a voltage sensing resistor and a current transformer. A current is induced into the resistor which is proportional to the voltage across the resistor. The current transformer is configured to sense the current passing through the resistor, where the output of the current transformer is a voltage proportional to the current. The result is a voltage sensor which has very high isolation but is limited to measuring AC signals. These sensors work very well for the dynamic, high voltage signals found in EM launchers.

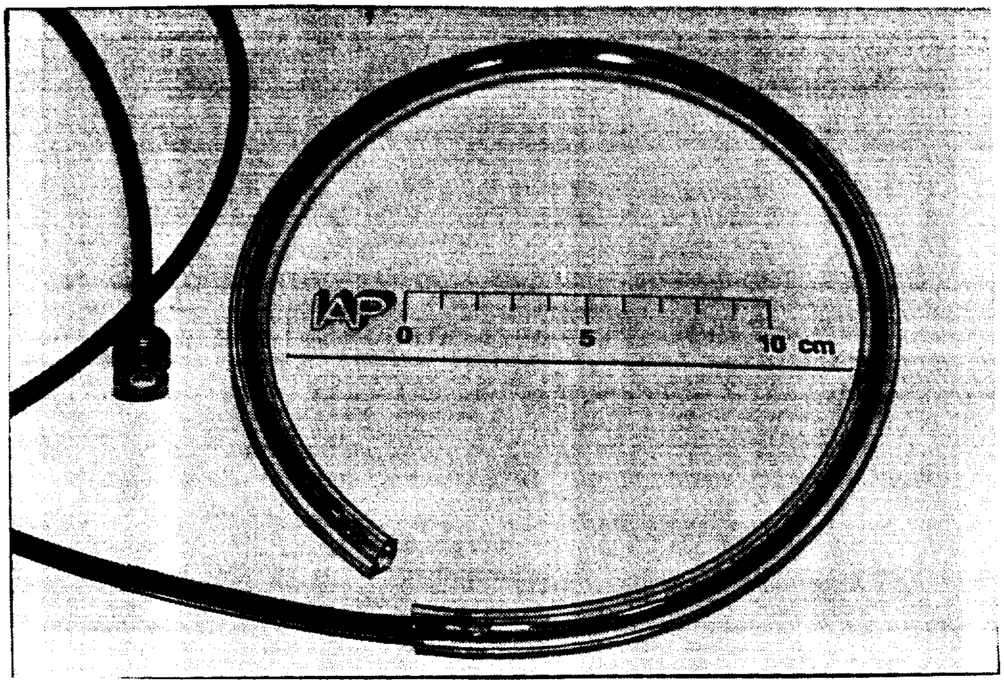

Figure 32. Rogowski coils were used to measure current within the system.

The voltage sensor used for this project was a custom design which was fabricated by IAP. A photo of one of the voltage sensor cards is shown in Figure 33. The performance of this sensor was comparable to a sensor which uses a high accuracy commercial current probe. An example of an X-Y comparison plot between the two sensors for launch data is shown in Figure 34. The IAP voltage sensors, costing roughly one eighth of the commercial sensor, gave us a low cost means for measuring the voltage at each stage power supply. We used our voltage cards during all testing with very good results.

4.1.3 Flight Range Velocity Sensors

We measured down range launch package velocity using a Magnetic Velocity Induction System (MAVIS). This system is passive and requires only that a small bit of conductor be embedded somewhere in or on the launch package. The system consists of two monitoring stations placed a fixed distance apart. The velocity is calculated from this distance and the recorded times at which the projectile is sensed at each station. Each station is simple in construction, consisting of a permanent magnet flux source and a sense coil. When a conductive material passes through the magnetic field at high velocity, it causes a change in the fields magnetic flux density which in turn induces a signal into the sense coil. A photo of one of the MAVIS stations is shown in Figure 35.

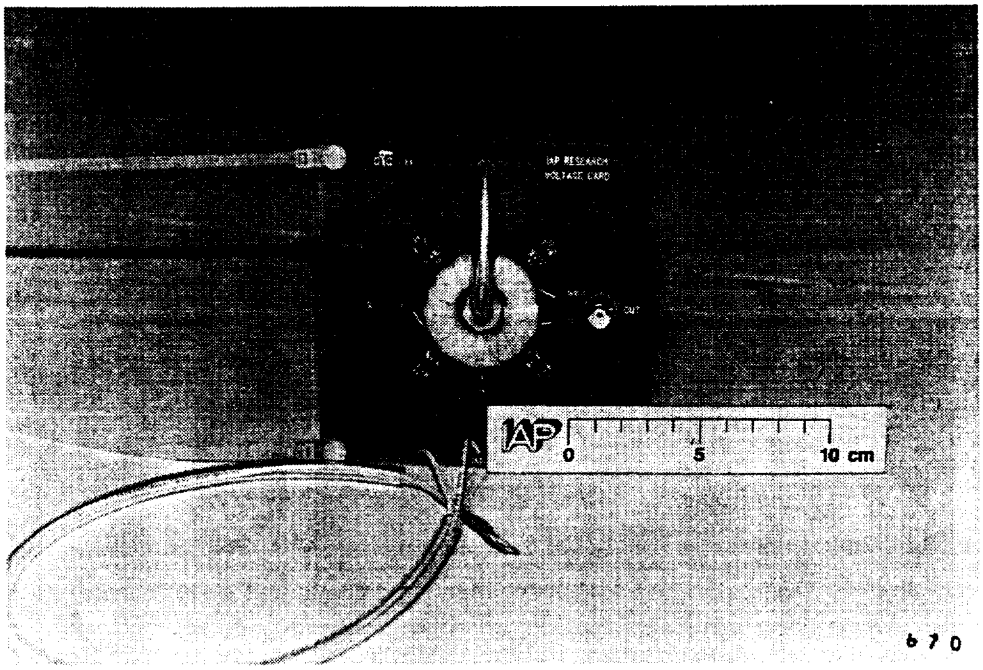

Figure 33. An example of the voltage probes used to measure stage supply voltage.

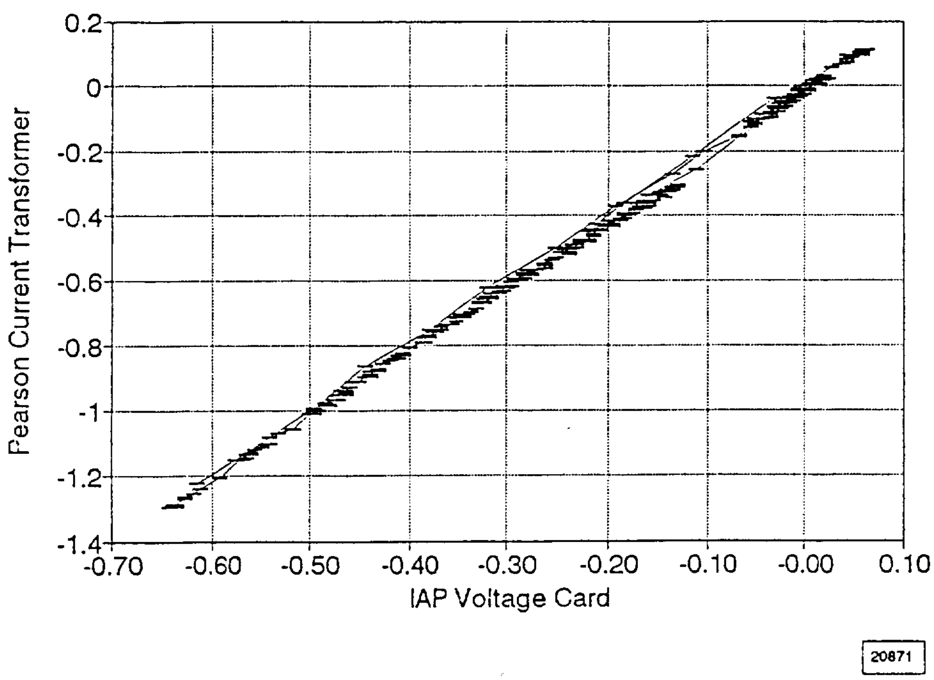

Figure 34. Our voltage card compared well with a commercially available Pearson probe.

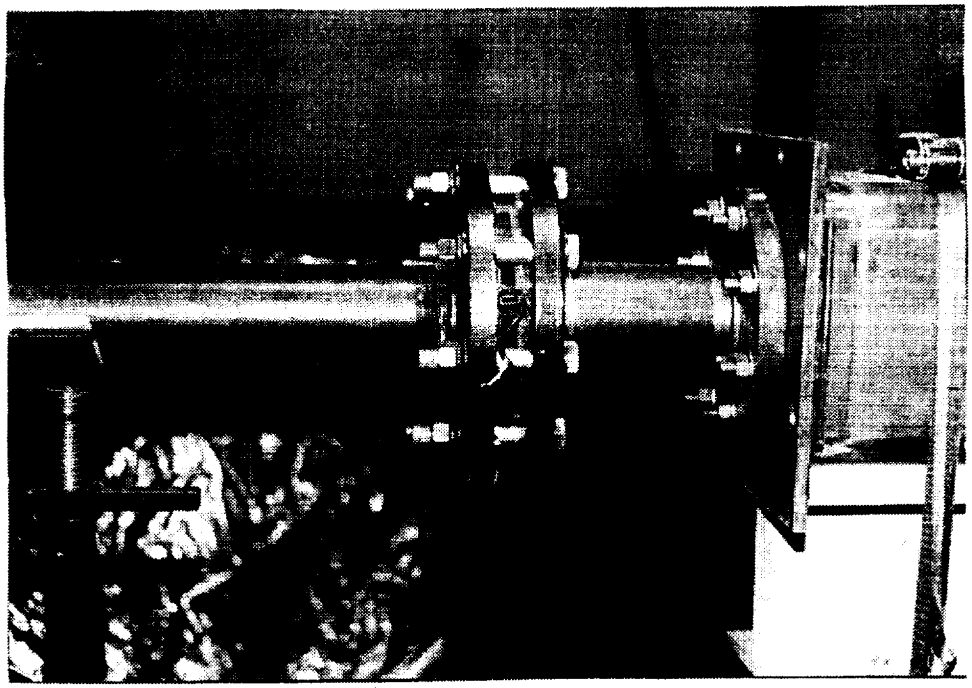

Figure 35. A MAVIS projectile sensing station.

Our plasma armature launch packages included an aluminum disk for providing a signal as it passed through the two magnetic (MAVIS) sensors. The signals we observed were very noisy and it was difficult to independently pick out the true launch package signal. The signal magnitudes were inconsistent as well, which we believe was due to tumbling of the launch package. The tumbling affects the projected cross-section of the disk as it passes through the field of the MAVIS, which in turn affects the signal level. Signals for metal armatures were good. Signals from plasma armature launch packages were weak, probably due to the thin, low mass aluminum foil used.

4.1.4 Bore Gauge

Before and after each launch we measured the variations in bore dimensions within the launcher. These bore dimension measurements provided us with wear characteristic data for the launcher and were used to determine when the launcher required rebuilding. A 19 mm bore gauge was designed specifically for use with the UDESS launcher. It used a strain gauge attached to a cantilever arm which deflected according to the bore dimension as it was pulled through the launcher. The gauge is shown in Figure 36. The gauge had a sensitivity of ± 0.0002 inches and a range of ± 0.04 inches (± 1 mm). The gauge included a calibration standard to verify these values prior to each use.

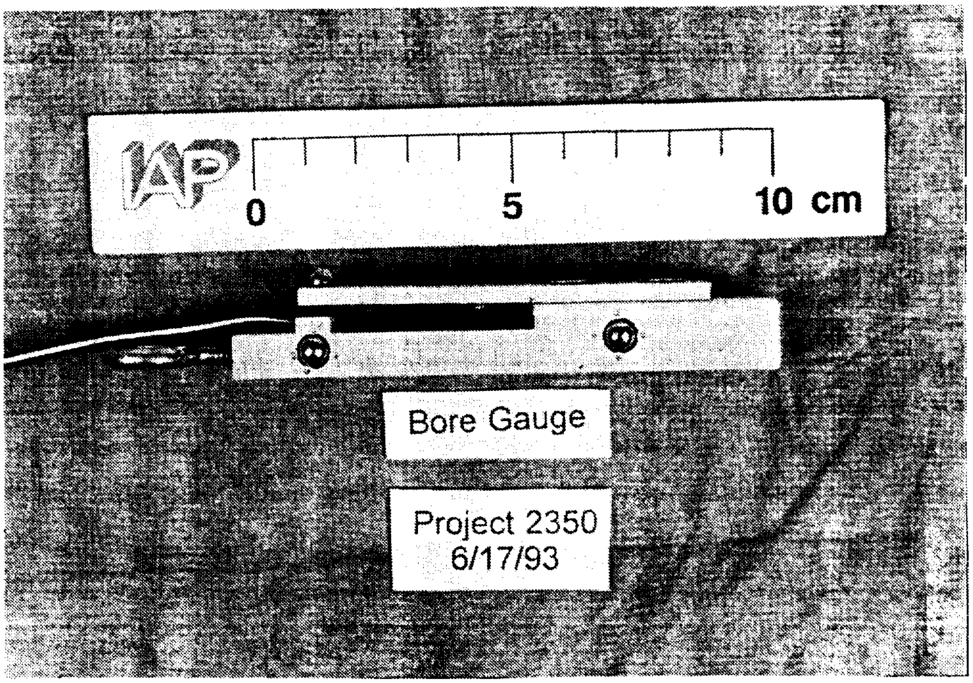

Figure 36. We used a bore gauge to monitor launcher dimensions during tests.

The bore dimensions measured for the launcher were very consistent. An example of a typical bore measurement is shown in Figure 37. This particular set of data was for a metal armature launcher which includes a 0.5 mm rail taper in the breech section. This shows up in the bore measurement starting at a distance of 3.05 m (120 inches) from the muzzle. The location of the DES feeds in the launcher can also be seen in this rail-to-rail bore measurement.

4.1.5 Break Wire System

A break wire system was utilized to monitor the velocity of the projectile within the injector. The break wire system was also used to initiate the discharge of the EM preaccelerator. This system is similar to the MAVIS system in that it incorporates a pair of projectile monitoring stations placed at a fixed distance apart. A very fine magnet wire (36 gage) is used by each station where, at the low velocities within the injector, this wire causes no problems to the launch package. Each position monitoring station was designed to recognize the breaking of the wire and provide the required 20 kV of electrical isolation. The break wire system is very simple and consistently provided good quality signals throughout this program.

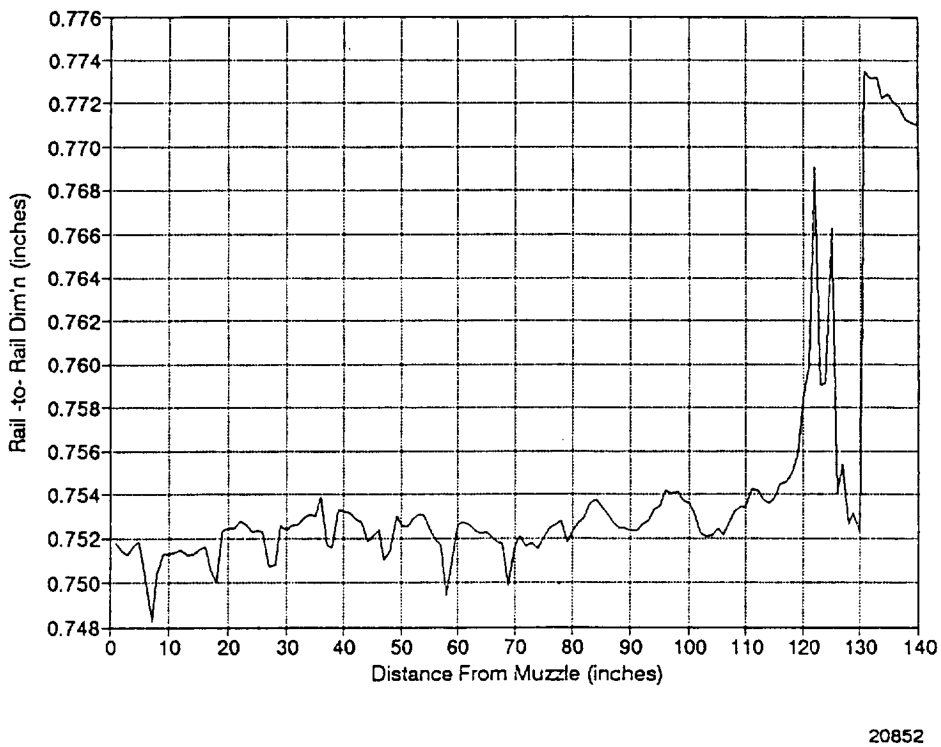

Figure 37. An example of bore measurement data.

4.2 DATA ACQUISITION HARDWARE

The complex UDESS launcher system required monitoring of a large number of signals, both to assure us that the system was operating properly, and to provide the data required to accurately characterize the system performance. Table 4 is a list of the signals which we monitored in a typical UDESS launch. From Table 4 it can be seen that for a full 32 stage launch, a total of 115 signals would be monitored. Many of these signals include high speed events which required high speed data acquisition equipment.

We utilized our existing laboratory data acquisition system during all tests. This system was limited to a maximum of 24 high speed channels. Budget constraints precluded acquisition of additional high speed recording channels. Instead, we developed a time multiplexing capability which allowed us to monitor multiple signals on each data acquisition channel. The multiplexers and our data acquisition system are described below.

TABLE 4. DATA ACQUISITION REQUIREMENTS FOR THE UDESS LAUNCHER

Recorded Parameter	Maximum Number of Channels Recorded	Resolution Required
BJ Module Currents	8	100 kHz
Launcher Breech Current	1	100 kHz
Launcher dI/dt	1	1 MHz
Stage Supply Currents	32	1 MHz
Breech Voltage	1	1 MHz
Muzzle Voltage	1	1 MHz
Stage Supply Voltages	32	1 MHz
B-dot Signals	35	1 MHz
MAVIS position Signals	2	1 MHz
Break Wire Signals	2	100 kHz

4.2.1 Data Multiplexers

Three data multiplexers were developed for recording data associated with the stage supplies, one each for stage currents, stage voltages, and stage B-dot signals. Each data multiplexer received data from 32 channels and provided 4 output channels of multiplexed data. After a stage had fired, and as the launch was progressing, each multiplexer was switched to monitor another stage further down the line. For example, one channel is used to output the signals from stage supplies number one, five, nine, thirteen, etc.

The data multiplexers allowed us to monitor the condition of all of the stages while utilizing fewer of our high speed data acquisition channels. A photo of one of the multiplexer modules is shown in Figure 38. The three multiplexers were integrated into the same rack with the discharge

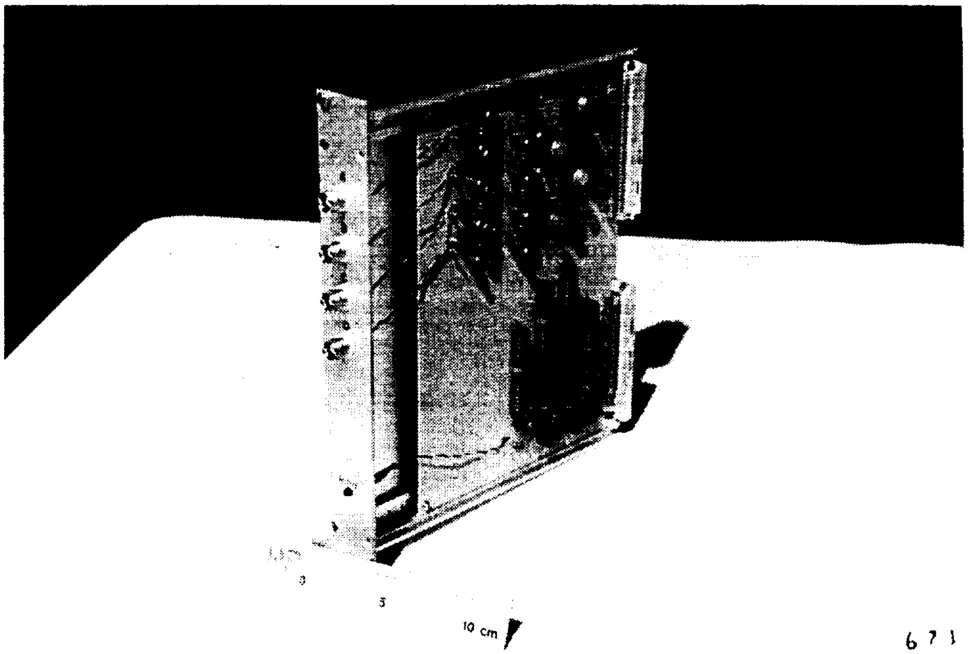

Figure 38. One of the three Multiplexer Modules.

controls. The signals into these modules were first passed through the buffer amplifiers described in Section 3 above. The data multiplexers were under the control of the stage sequence controller. To aid in the interpretation of the time multiplexed data, a double strobe pulse was superimposed upon the output signal whenever a channel was switched. These markers allowed the data from each channel to be separated in post processing.

4.2.2 Data Acquisition System

We utilized our CAMAC standard laboratory data acquisition system during launcher testing. This system consists of 24 high speed (1 MHz) channels and 32 low speed (100 kHz) channels under PC control. The system is capable of acquiring up to 8000 points per channel and can be configured for any split in pre-trigger and post-trigger samples. The software which controls this system is IAP custom software, developed over the past ten years, which is specifically designed for acquisition of data from EM launcher systems. The software has been tailored for rapid setup and control of an experiment and allows us to configure the data acquisition system in a minimum time period. This software also includes a number of signal conditioning (filtering, integration, offset subtraction, etc.) analysis (FFT, statistics, graphing), and conversion algorithms.

4.3 DATA ANALYSIS

To characterize the UDESS system we first performed a of baseline launch where the DES portion of the launcher was not energized. Due to the fact that our UDESS system used continuous rails, the system could be operated as a normal breech-fed EM launcher when the DES supplies were not enabled. The second step in system characterization was to perform an identical launch, with an identical launch package, with the DES portion of the launcher energized. This test method was used for both injected and standing start launches of both plasma and metal armature launch packages.

This test method allowed us to make a relative assessment of the performance of the UDESS system with respect to a conventional breech-fed launcher of identical configuration. For the plasma armature launches there was minimal damage to the rails after the baseline launches. We were able to clean the launcher and perform the DES launches without rebuilding. Metal armature launches required that the launcher be rebuilt with a new set of rails for best accuracy.

We performed analysis on the acquired data to characterize the UDESS EM launcher. The UDESS system was conceived in response to the velocity limit found in plasma armature EM launchers. Our primary interest was to determine the characteristics of the plasma armature and to measure its response to the distributed energy section of the launcher. Our secondary interest was to assess the launcher performance when launching a metal armature launch package. The launcher performance characteristics which we analyzed are described below.

4.3.1 Launch Package Position and Velocity

Launch package position data for a launch was compiled from the break wires, B-dot sensors, and the MAVIS sensors. Each time the launcher was assembled, the locations for each sensor were accurately measured and recorded. After a launch, the recorded time histories from these sensors were used to generate position versus time plots and velocity versus time plots. Examples of typical position data and velocity data are shown in Figures 39 and 40.

4.3.2 Armature Current

The armature current was determined by summing the total current from the EM pre-accelerator with the individual stage supply currents. An example of armature current data is shown in Figure 41. From this data the contributions from the individual stages can be clearly seen. At about the 6.7E-3 second point on this time history the armature exits the launcher, as evidenced by a sharp break in the

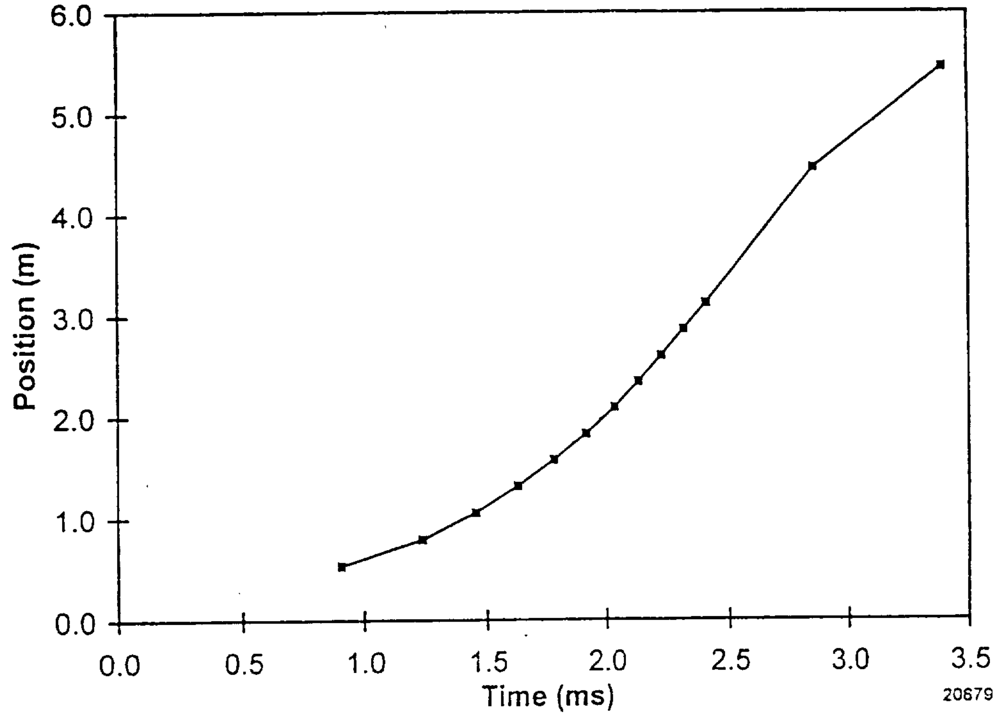

Figure 39. **An example of typical position data from a launch.**

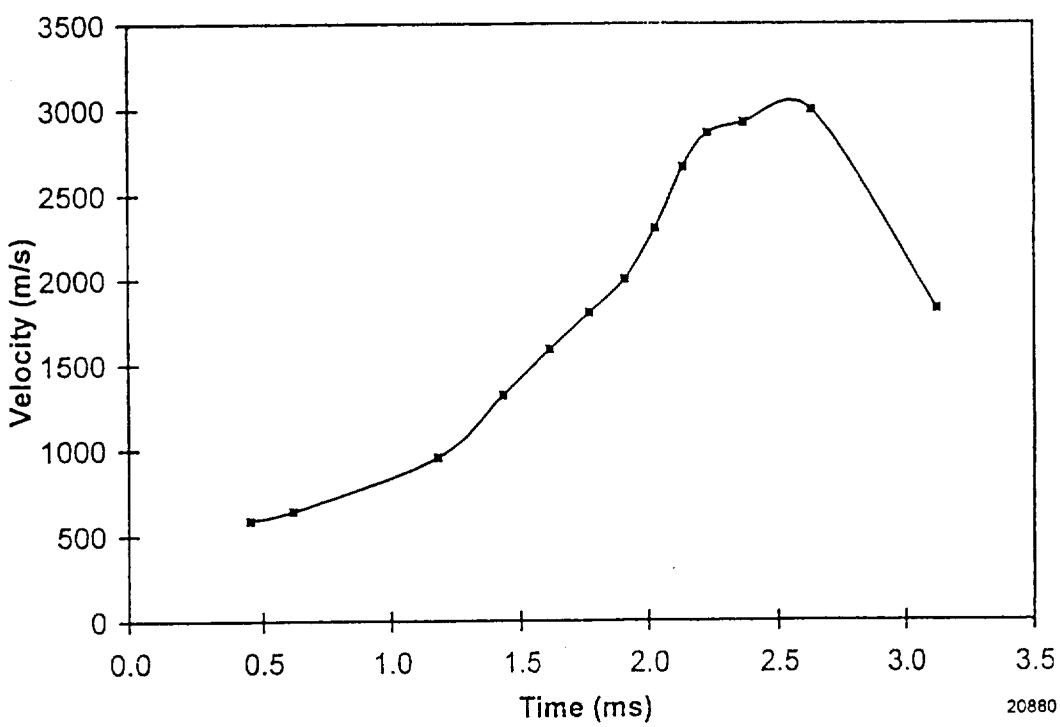

Figure 40. **An example of typical velocity data from a launch.**

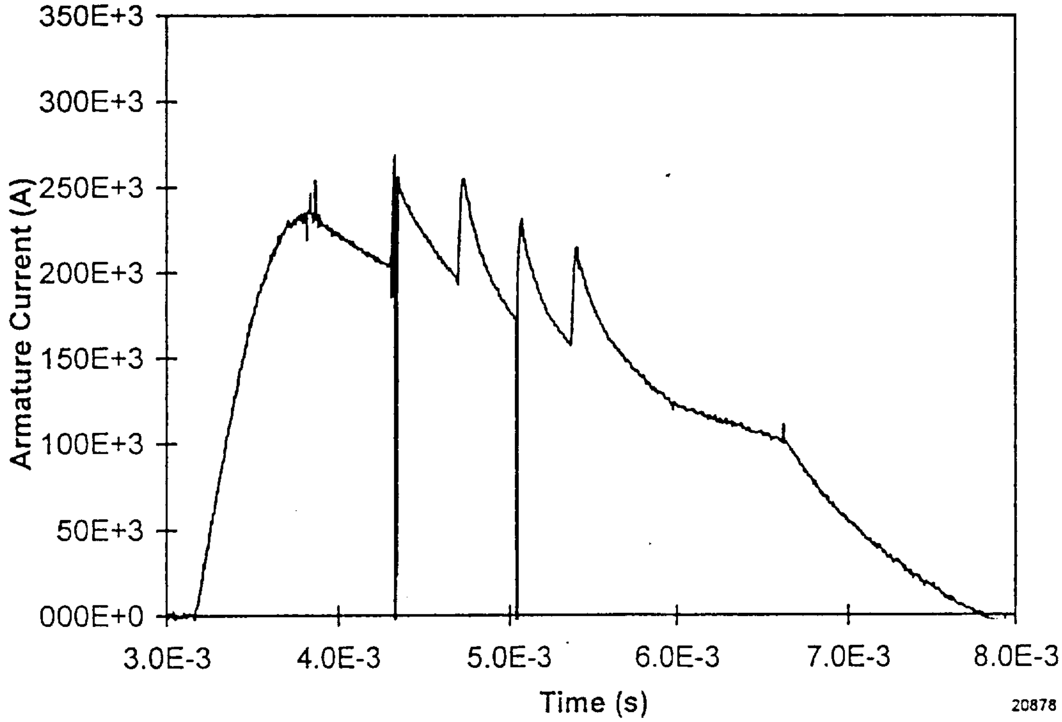

Figure 41. An example of armature current data from a launch.

current waveform. This characteristic response occurs as the remaining stored energy in the system is dissipated in arcing at the muzzle of the launcher.

4.3.3 Armature Voltage

The armature voltage was assumed to be equal to the voltage recorded at the muzzle of the launcher. As long as no current is flowing in the rails in front of the armature this assumption is valid. The armature voltage for a metal armature should remain very low, typically less than 20 volts. If the armature contact breaks down and begins to arc, the armature voltage will experience a sudden jump in magnitude. For the UDESS launcher, a plasma armature had a recorded voltage of typically around 200 volts. It is desirable for the armature voltage to remain at a fairly constant value throughout the launch. An increasing armature voltage indicates that the armature is becoming less conductive due to the plasma becoming less compact behind the projectile. An example of armature voltage data for a typical plasma armature UDESS launch is shown in Figure 42.

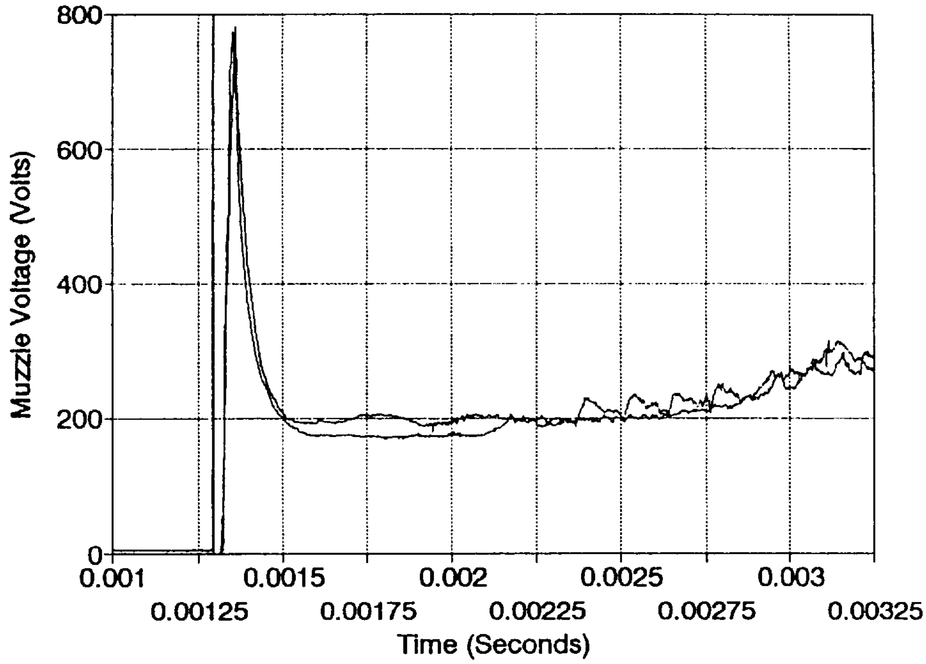

Figure 42. An example of armature voltage data from a UDESS launch.

4.3.4 Rail to Rail Voltage

The breech voltage represented the rail to rail voltage for the longest length of the EM launcher. We had previously determined a requirement that, for the UDESS launcher, this voltage must remain below 800 volts to prevent the formation of secondary armatures. An example of measured breech voltage data for a plasma armature launch is shown in Figure 43. Shown is an overplot of the baseline launch data and UDESS launch data. This data is typical of a plasma armature where there is a large initial voltage as the plasma is initiated with the blowing of the fuse.

We also analyzed the voltage recorded at the stage supplies. An example of stage supply voltage data for a plasma armature launch is shown in Figure 44. The data shown in Figure 44 is an overplot of the breech, muzzle, and stage supply data. The characteristics shown for this stage supply voltage were typical. Initially the voltage at each stage was equal to the muzzle voltage. As the armature began to pass the location of the voltage sensor, the stage supply voltage begins to rise. When the stage supply fires the waveform shows a voltage spike, due to launcher and supply inductances, followed by rapid settling to a level approximately equal to the breech voltage. For launches in which the DES is disabled, the waveform is similar, the only difference being that the spike is missing.

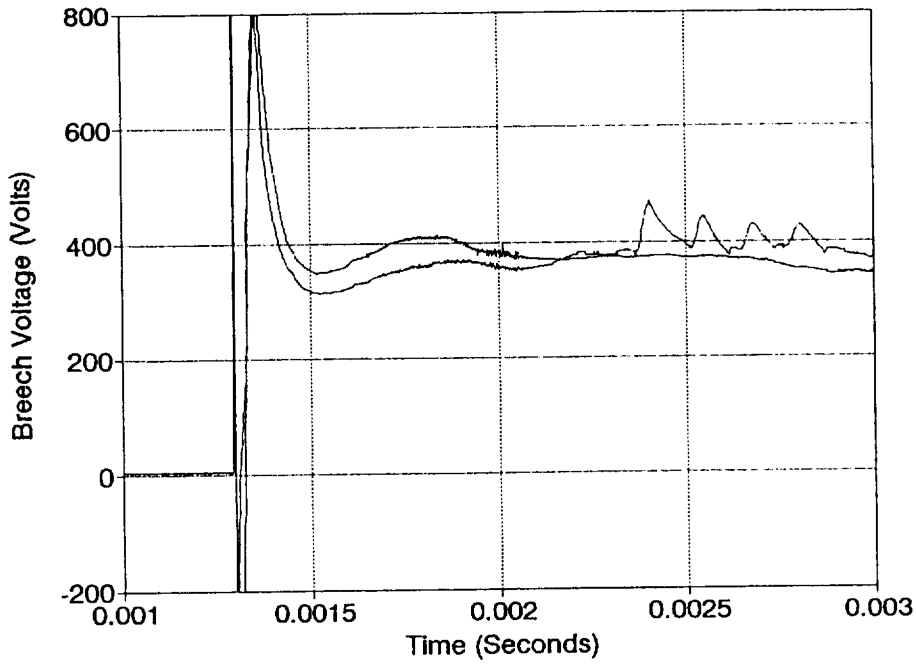

Figure 43. **An example of breech voltage data from a plasma armature launch.**

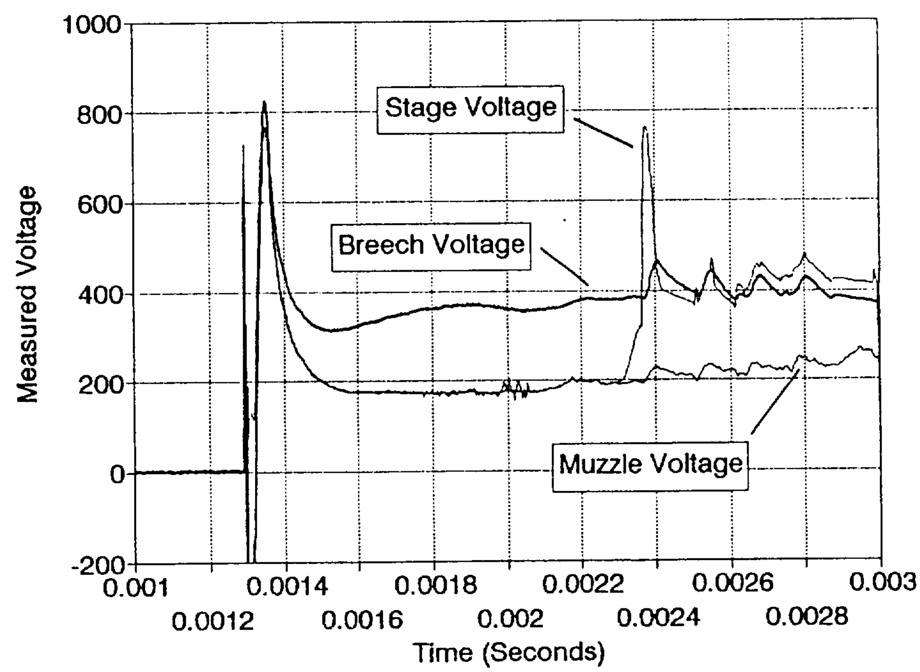

Figure 44. **Typical stage supply voltage response for a plasma armature launch.**

This characteristic response was also found with metal armature launches, including the voltage spike when the supply fired.

4.3.5 *Plasma Armature Compactness*

We analyzed the data from the B-dot probes to quantify the compactness of the plasma armatures. First, we integrated the B-dot signals to determine the total barrel flux at each sensor location. The barrel flux is directly related to the total current in the launcher where the two signals will track when the armature is well past the sensor location. We normalized the launcher flux signals to the total launcher current signal and measured the time it takes for the flux signal at the probe to equal the total current signal. As a standard procedure, we took the time between when the normalized signal is 0.1 and 0.9 of the total current. We then multiplied this time by the armature velocity to obtain armature length.

The ideal response, for a barrel flux signal at any sensor location, would show a very fast rise time followed by close tracking of the current signal profile. This response would indicate a very compact armature with little residual current flow behind the armature. With the addition of the current signals from the stage power supplies we were able evaluate the nature of the plasma armature further. The location of the armature with respect to the feeds of the stage power supplies effected the direction of current flow when a stage power supply was fired. The desired response is for all of the current from the stage to flow in the part of the launcher that is between the supply feeds and the muzzle. Long armatures will have current flowing in both the muzzle and breech ends of the armature, where the flux in the barrel will be increased in the muzzle end of the launcher and decreased in the breech end.

An example of barrel flux data for a plasma armature UDESS launch is shown in Figure 45. This data shows the barrel flux at the B-dot sensor location 0.25 meter before the UDESS portion of the launcher followed by the barrel flux data at the location of the first two stages of the UDESS. The data shows a clear increase in the barrel flux when a stage supply fires. As each stage supply fires, the data also clearly shows the effects of reverse current flow and a corresponding decrease in barrel flux at the location of the first B-dot sensor. The magnitude of this decrease in flux and the number of stage supplies which effect this signal is directly related to the conductivity versus length profile for the plasma armature.

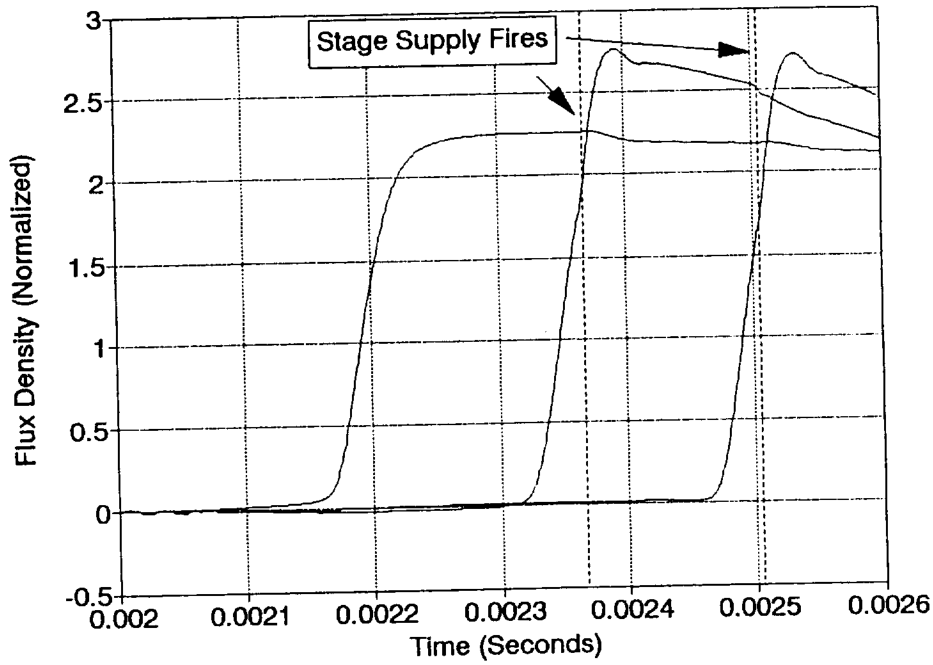

Figure 45. An example of barrel flux data for a plasma armature UDESS launch.

4.4 LAUNCH SUMMARY

Table 5 contains a summary of the launches performed over the duration of this program. Not shown in this table are the shorting tests which were performed before each launch. These tests were used to test the UDESS hardware as well as for troubleshooting purposes. The number of shorting performed over the course of this program was greater than 75. For shorting tests in which the UDESS portion of the launcher was enabled, the UDESS supplies would fire in sequence, where the supplies fired at the time corresponding to the opening of their firing window. Table 5 is a summary of the launches which apply to the UDESS launcher system and does not include tests which were performed during launch package design. These tests were performed in a separate launcher which did not include the UDESS stage.

TABLE 5. LAUNCH SUMMARY

Description	Launch Package	UDESS	Result
1. Baseline launch	Injected plasma 5 g	4 supplies not connected.	Good launch.
2. Baseline launch	Injected plasma 5 g	4 supplies connected but disabled.	Good launch. Long armature observed
3. UDESS launch	Injected plasma 5 g	4 supplies enabled.	Good launch. Distinct secondary formation due to projectile breakup. Supplies fire in proper sequence.
4. Baseline launch to test projectile.	Injected plasma 5 g	4 supplies disabled.	Projectile appears to break up again. Distinct secondary formation.
5. Baseline launch	Injected plasma 10 g	4 supplies disabled.	Good launch. Some problems with the data acquisition system causes loss of data.
6. Baseline launch	Injected plasma 10 g	4 supplies disabled.	Good launch.
7. UDESS launch	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate. All data acquired is corrupted.
8. UDESS troubleshooting	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate properly.
9. UDESS troubleshooting	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate properly.
10. UDESS launch	Injected plasma 10 g	4 supplies enabled.	Good launch.
11. UDESS launch	Injected plasma 10 g	4 supplies enabled.	UDESS controls fail to operate properly.
12. UDESS launch	Injected plasma 10 g	4 supplies enabled.	BJ bank prefires, destroys breech.
13. Baseline launch	Stationary metal	4 supplies disabled.	Good launch.
14. Baseline launch	Stationary metal	4 supplies disabled.	Good launch.
15. UDESS launch	Stationary metal	4 supplies enabled.	Good launch.
16. UDESS launch	Injected metal	4 supplies enabled.	Good launch.
17. Armature test with BJ ripple fire	Stationary metal	Supplies disabled.	BJ ripple incorrect. Armature transitions. Range severely damaged.
18. Armature test	Injected metal	4 supplies enabled.	BJ delay incorrectly set. Launcher damaged in area of breech.
19. Armature test	Stationary metal	Supplies disabled	Good launch.
20. Armature test	Stationary metal	Supplies disabled.	Good launch.
21. Armature test	Injected metal	Supplies disabled.	BJ bank prefires causing severe damage to the launcher.
22. Armature test	Injected metal	Supplies disabled.	BJ bank prefires causing severe damage to the launcher.
23. Armature test	Injected metal	Supplies disabled.	Good launch.
24. Armature test	Injected metal	Supplies disabled.	Good launch.
25. Baseline launch	Injected plasma 10 g	8 supplies disabled.	Good launch.
26. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Good launch, some data acquisition problems.
27. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Launcher voltage breakdown, some UDESS supplies do not fire.
28. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Good launch.
29. UDESS launch	Injected plasma 10 g	8 supplies enabled.	BJ bank module fails, some UDESS supplies do not fire.
30. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Good launch, some data acquisition problems.
31. UDESS launch	Injected plasma 10 g	8 supplies enabled.	Strong secondary armature formation, UDESS controls do not trigger.

From Table 5 it can be seen that we performed a large number of launches. It is also apparent that several problems occurred during system development and testing. The launcher was tested with a maximum of eight UDESS stage supplies. However, with the eight stage system, we had observed performance which indicated that the launcher, as implemented in this program, was not reducing secondary formation and that a greater number of stage supplies would not improve this situation. In Section 5 we discuss the results of our testing and make recommendations on how future electromagnetic launchers may be improved based upon our observations.

SECTION 5

DISCUSSION OF UDESS PERFORMANCE AND TEST RESULTS

In this section we present the results of the UDESS experiments in relation to predicted performance, discuss the significance of these results with respect to future EM launcher development, and make recommendations on where the UDESS system may be improved.

5.1 DISCUSSION

The primary goal for this program was to show that the UDESS system was effective at eliminating secondary armature formation during plasma armature launches in an EM launcher. Under ideal plasma armature launch conditions, a single compact armature is maintained in close proximity to the launch package. The elimination of the secondary armatures enables the launcher to attain hypervelocity performance. The results of our experiments with the prototype UDESS system indicated that this system was not effective at eliminating secondary armature formation. The UDESS system, as conceived and implemented for this program, appeared to have detrimental effects upon the plasma armature and may have actually increased the likelihood of secondary armature formation. There were several factors which contributed to the failure of the prototype system to produce the desired improvements in EM launcher performance. The most significant of these factors being the length of the plasma armature.

The problem with the UDESS is directly related to the length of the plasma armature. We discovered that the plasma armature was significantly longer than the length which was generally accepted. The effects of the UDESS system upon this armature were not positive. When a UDESS stage supply was fired close to the armature peak, it caused the armature to spread due to reverse current flow. When a UDESS stage supply was fired soon after the main armature had passed, it caused a secondary armature to form in the highly conductive plasma which trailed the main armature. Finally, the UDESS stage supplies were designed with low inductance (2 μH) to allow for fast current rise time and subsequent fast current decay time (desired to reduce rail-to-rail voltage). Firing a UDESS supply after the armature was well past the power supply feeds resulted in a high voltage across the stage feeds due to the EM launcher inductance (approximately 0.4 μH/m).

With our prototype system, there was basically no good timing point at which the stage supplies could be fired and have a positive effect upon the plasma armature. The system as conceived for this program could not be easily modified to overcome this problem. In the sections below we discuss our observations in greater detail and describe the limitations of our prototype UDESS system.

5.1.1 Armature Length and Reverse Current Flow in the UDESS Launcher.

When the UDESS program began there was limited detailed information available about the nature of plasma armatures in EM launchers. Specifically, the conductivity of the plasma with respect to distance behind the launch package had not been thoroughly investigated. It had been generally accepted that the majority of the current flow in the armature occurred within one quarter of a meter of the launch package. During this program we learned that, while the majority of the current flow does occur within the first quarter meter, the effective current carrying length of a plasma armature was substantially longer.

The UDESS system was an effective tool for probing the plasma armature. By injecting a current into the launcher soon after the launch package had passed, we were able to evaluate the conductivity of the plasma. It was desired that the vast majority of the stage supply current would flow in the forward direction in the launcher when the stage power supply was fired within a quarter of a meter from the launch package. The level of reverse current flow in the launcher rails is determined by the conductivity of the plasma that is between the breech of the launcher and the stage power supply location. B-dot probes spaced every quarter meter in the launcher allowed us to monitor the current flow within the launcher and provided a measure of the conductivity gradient with respect to distance behind the stage power supplies.

Our experimental results indicated that the plasma armature length during our launches was initially very long, that is, the entire preaccelerator was filled with conductive plasma. Our system included an EM preaccelerator, one meter in length, which preceded the UDESS launcher. At the very first stage supply location in the UDESS, we observed that the plasma armature from the preaccelerator was not compact. Indications of reverse current flow could be seen at B-dot locations in excess of one meter behind the stage power supply feeds. An example of data from the B-dot location directly before the UDESS portion of the launcher is shown in Figure 46. The B field at this location in the launcher was reduced as each stage power supply down the launcher was fired. The level of field reduction was indicative of the amount of current conduction occurring between this B-dot location and the breech of the launcher. The consequence of this reduction in B-field was that any plasma that was behind the stage power supply being firing was not accelerated at the same rate as the plasma which was in front of the stage feeds, resulting in a spreading of the plasma armature.

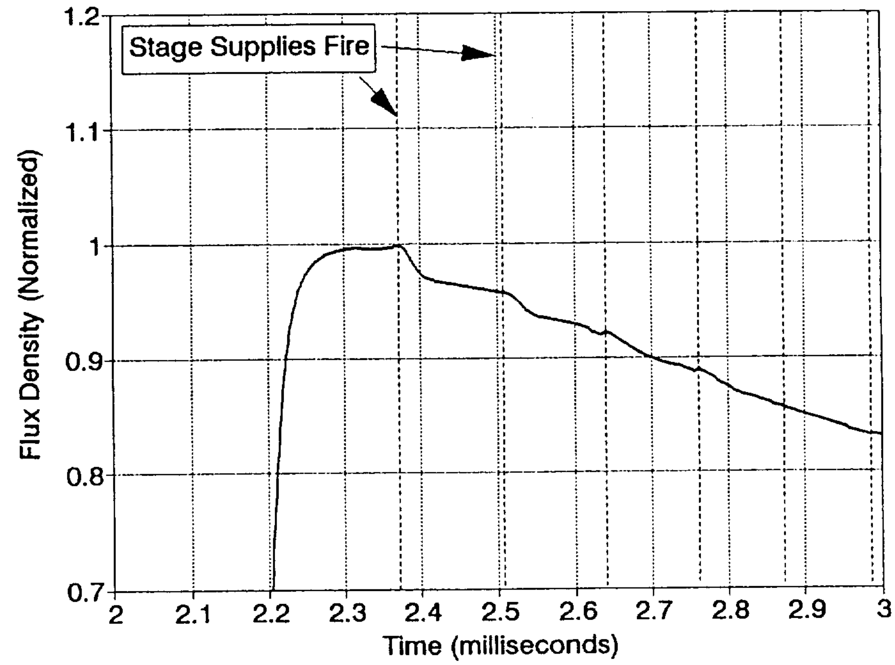

Figure 46. Reverse current flow results in reduced B-field behind the stage power supply.

During a plasma armature launch within the UDESS system, the armature became less compact as the launch progressed. The gradient of the conductivity with respect to distance behind the launch package decreased as the launch progressed. Again, we were able to assess the level of current conduction behind the launch package by monitoring the changes to the B-dot signals as the stage power supplies were fired. We observed an increase in the level of reverse current flow as the launch progressed at the B-dot locations behind the stage power supply being fired.

To minimize the spreading of the plasma armature due to reverse current conduction, each stage power supply should be fired after the majority of the current conducting plasma has passed the stage feeds. However, due to the long length of the armature, waiting to fire the stage supplies leads to a new set of problems, as described below.

5.1.2 Secondary Formation in the UDESS System.

During the course of our experiments we experienced several launches where secondary armatures formed. During some of our initial experiments we had some problems with the launch package breaking up, causing the armature to spread, and leading to secondary formation. We performed several launches before we were able to determine that the launch package was indeed breaking up. In all of our launches, the range catch tank destroyed the launch package. We tried several methods to provide a "soft" landing for the launch package, but none were successful. Basically, the launch package was reduced to scraps, leaving us with no physical evidence of launch package integrity during an experiment. Ultimately, inspection of the launcher revealed projectile breakup was occurring. The solution was to increase the strength of the launch package with a corresponding increase in its mass.

The second instance for secondary armature formation observed in the UDESS launcher occurred when a stage power supply was fired after the plasma armature was past the stage feeds, but within a quarter of a meter of them. Data illustrating this secondary formation is shown in Figure 47. During this launch, the firing time for the stage power supply was delayed until after the B-dot signal had returned to a low level, a point at which the B-field had stabilized behind the armature, indicating that the majority of current was flowing in front of the stage feeds. When the stage supply was fired there was an increase in the B-dot signal as expected. However, as the stage supply fires there is also a second armature which is formed at the location of the stage feeds. The second B-dot signal, corresponding to the location of the next stage power supply down the launcher, shows the two distinct armatures, with the second armature now carrying the majority of the current.

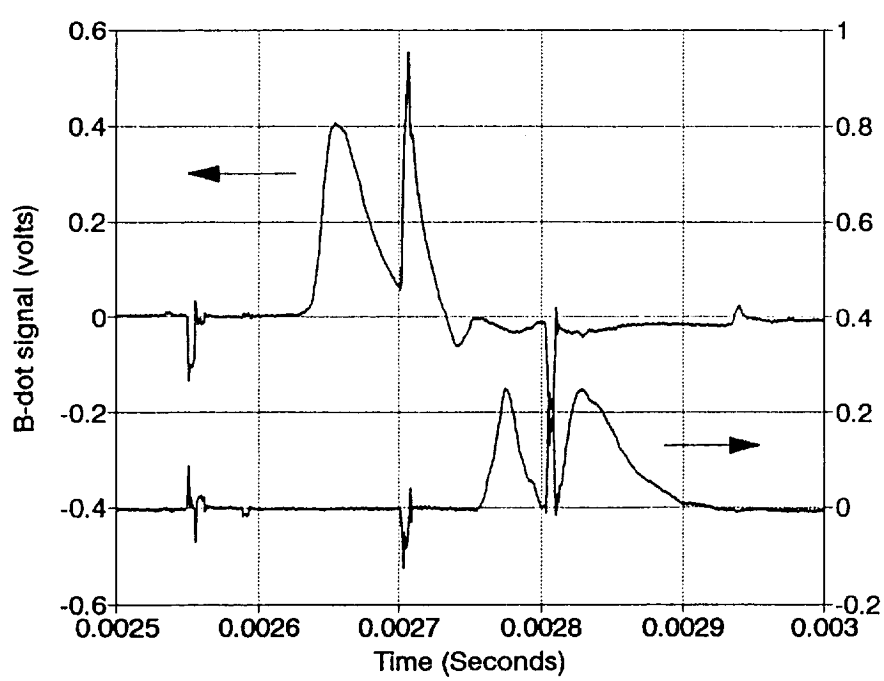

Figure 47. The UDESS system can cause secondary armature formation.

As discussed in Section 5.1.1, the plasma behind the launch package is very conductive for a distance over one meter behind the launch package. It appears that the conductivity of this plasma is such that, when combined with the inductance of the launcher, current will flow directly across the launcher when the stage supply is fired. The current is following a path which offers the least impedance, where the inductance of the launcher presents a higher impedance to current flow than the resistance of the plasma across the stage supply feeds.

The plasma armature has a gradient to its conductivity, where the conductivity of the plasma decreases with increasing distance behind the launch package. At some point behind the armature the conductivity drops to a level where a stage supply may be fired and the resulting current flows forward in the launcher to the main armature and no secondary armature forms. Unfortunately, the design of the UDESS stage power supplies do not allow them to be fired when the armature is well past the stage feeds. In this case a large rail to rail voltage forms, as described below.

5.1.3 Rail to Rail Voltage.

We have already described how a large rail to rail voltage is undesirable in an EM launcher. We have determined that the rail to rail voltage in the UDESS launcher should be maintained below 800 volts (for a 20 mm bore size) in order to prevent secondary armature formation. The power supplies that are typically used in EM launchers have capacitive energy stores, where the stored energy is equal to $1/2CV^2$. The capacitors are high voltage capacitors, in the UDESS system the capacitor voltage could be as high as 10 kV. When a launcher power supply is fired, this high voltage is applied across the supply inductor and the launcher. Typically, the impedance of the supply inductor is substantially higher than that of the launcher and the majority of this voltage is seen across the inductor. The UDESS stage supplies do not have a high value of supply inductance. This limits the impedance of the launcher to a low value in order to maintain a low rail to rail voltage.

When the UDESS system was conceived, it was anticipated that the length of the launcher which would be powered by each stage power supply would be approximately one quarter of one meter. The stage supply inductor was sized to provide the highest dI/dt while still insuring that the launcher voltage remain below 800 volts. The resulting stage inductance was 2 μH and the launcher inductance gradient was 0.4 μH per meter. For the maximum charge voltage of 10 kV, the voltage developed across the stage supply feeds would be 500 volts when powering one quarter meter of the launcher. The launcher inductance gradient and voltage levels were verified during shorting tests of the launcher. An example of shorting test data is shown in Figure 48. A 1.25 meter long section of launcher has a total inductance equal to 0.5 μH and the voltage developed across the stage feeds should equal one fifth of the applied voltage.

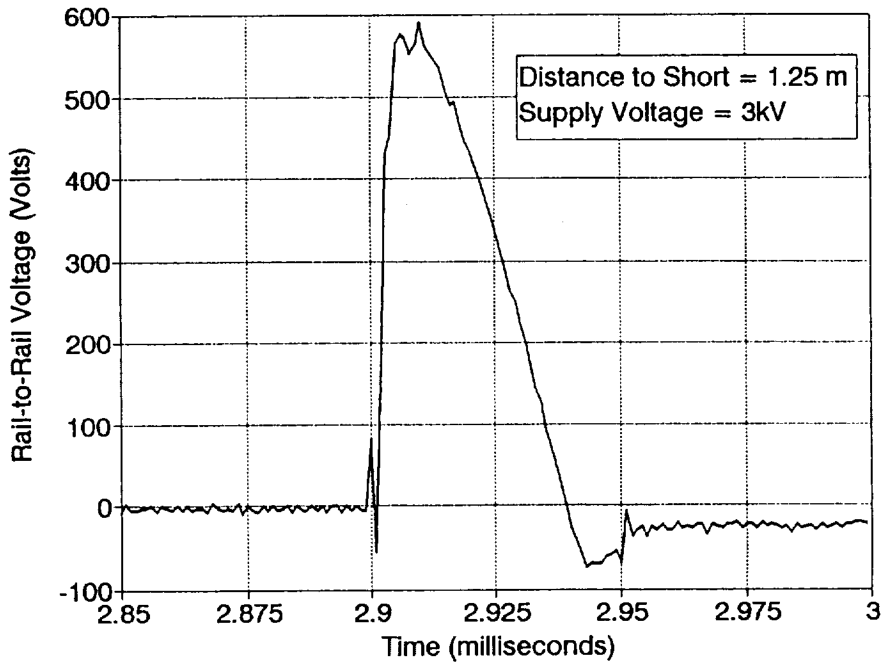

Figure 48. The inductive voltage at the stage supply feeds for a shorting test.

The total length of launcher which may be powered by a stage power supply is limited by the supply charge voltage and the requirement that the launcher voltage remain below 800 volts. For a stage supply charge voltage of 10 kV, the length of launcher which is powered should not exceed 0.42 meters.

Under our original concept for system performance, we had predicted that the UDESS system would be effective at reducing the rail to rail voltage within the launcher, where the breech voltage should experience the greatest reduction in this voltage. During this program, we did not observe any significant differences in rail to rail voltages between the UDESS shots and the baseline breech fed launches. Figure 49 is an example of an overplot of breech voltage data comparing a UDESS launch to its baseline breech fed launch. Because the system was never tested to its full 32 stage capability, due to the problems described above, we could not experimentally validate reduction in rail to rail voltage due to negative dI/dt contributions from the stage power supplies.

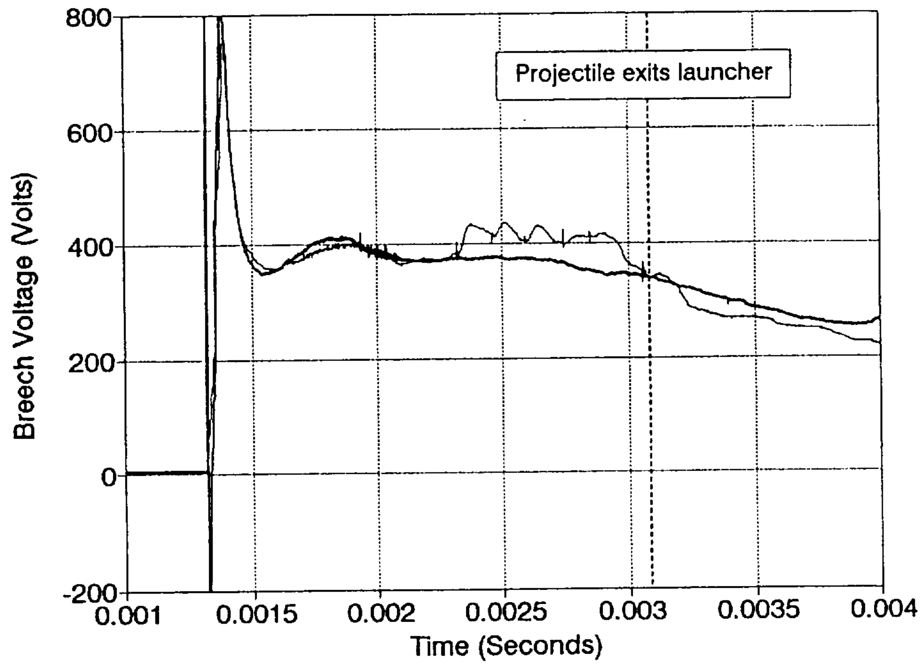

Figure 49. The breech voltage was not significantly reduced by the UDESS system.

We observed that the rail to rail voltage at the stage power supply locations was initially equal to the muzzle voltage. As the armature passed the stage power supply the voltage would then very rapidly approach a level equal to the breech voltage, whether during a UDESS launch or breech fed launch. This observation verifies the prediction that the dominant mechanism for rail to rail voltage is not related to the position of the armature in the barrel but rather is dominated by the velocity of the armature. The high velocity attained from the EM preaccelerator and the resulting voltage tended to mask any reductions in the rail to rail voltage which may have been seen during a UDESS launch.

5.1.4 System Efficiency.

The secondary goal for the UDESS program was to determine if the UDESS system could improve the efficiency of EM launchers. The system efficiency is defined as the percent of the total launcher energy input which is converted into launch package kinetic energy. To show that the system efficiency has improved, it must be determined that for the same total energy and launcher conditions (launch package, bore size, length), the launch package velocity is higher with a UDESS system as opposed to a normal breech fed system. We were not able to attain an accurate determination of improved system efficiency with the eight stage system.

Our experimental data did not allow us to reliably assess the system efficiency for basically the same reasons that we could not accurately assess the reductions in rail to rail voltage in the UDESS system. The high magnitude of our EM preaccelerator current, combined with the high plasma armature voltage, dominated the response of the system. This fact combined with the normal launch to launch variations in current and voltage levels in the EM launcher, and unreliable recording of velocity information, did not allow us to draw any concrete conclusions about system efficiency. We did observe some evidence of increased velocity during UDESS launches over the baseline breech fed launches. We could not accurately determine whether this increase was due to the increased energy from the UDESS, or if it was simply due to normal launch to launch variations.

Metal armature launches in the UDESS system have the greatest potential for allowing the system efficiency to be evaluated. The voltages in the system are significantly lower during metal armature launches and any recorded signals tend to be significantly less noisy than those recorded during plasma armature launches. To accurately assess the efficiency of the system, the EM preaccelerator current level would need to be significantly reduced during a UDESS launch so that the energy level could be matched to the baseline breech fed launch.

5.2 APPLICATION OF RESULTS TO EM LAUNCHER TECHNOLOGY

While the overall performance of the UDESS experiment did not meet our expectations for the system, there were several results which can be used to further advance the state of EM launcher technology. Perhaps the most important of these results is that we showed that the launcher current waveform can be controlled and altered during the course of a launch. The technique of monitoring the position of the armature during the course of the launch and tailoring the driving current waveform can be used in conventional breech fed railguns which utilize multiple power supplies as well as variations on the UDESS theme. The use of the B-dot signals to determine armature position worked very well and can be readily improved upon. For the UDESS program we utilized straightforward analog signal processing to control the triggering of our stage power supplies. However, the relatively slow launch times (as compared to the speed of modern electronic processors) allow the integration of smart signal processing which could greatly improve system performance. Our UDESS control system was designed such that a smart launcher could be implemented by replacing a single module.

The UDESS system was conceived as a technique for improving the performance of EM launchers which utilize plasma armatures. The goal was to attain velocity performance in excess of 6 km/s; to break the velocity "speed limit". The theoretical potential for EM launchers to attain velocities in excess of what is possible with conventional light gas guns makes their development attractive for hypervelocity applications. There are other major benefits to EM launchers for applications with lower velocities as well. Perhaps the strongest argument for the development of EM launchers is that, from a logistics standpoint, they allow for the elimination of propellants, EM launchers requiring only some source of electrical energy. The lower velocity application of EM launchers can utilize metal armatures, for which a UDESS type system may work very well.

A UDESS system which is launching metal armatures can be designed to trigger the stage power supplies in very close proximity to the metal armature. The problems of reverse current flow and secondary formation would not be factors with the absence of the plasma. The efficiency for this system could theoretically be very high as each stage power supply would be powering only a short section of the launcher. The B-dot signals observed during metal armature launches tend to be very clean, allowing for reliable determination of armature position within the launcher.

During this program we learned that the plasma armatures generated in our system had a strongly conductive region with a length exceeding one meter. The conductivity in this region had a steep gradient with respect to distance behind the launch package. This gradient changed during the course of a launch, becoming less steep as the launch progressed. If plasma armatures are to be utilized within EM launchers, and if development of the UDESS concept is to be continued with plasma armatures, then more information about the nature of plasma armatures is required. A technique for evaluating the nature of a plasma armature during the course of a launch can be developed using a system similar to the UDESS system.

We were able to evaluate the plasma armature during the UDESS launches by injecting a fast changing current into the launcher. A similar technique can be utilized for researching the characteristics of plasma armatures during EM launches. The magnitude of the injected current can be maintained at a low level while the high dI/dt associated with the waveform allow it to be readily sensed by B-dot probes. Injecting this current at some distance in front of the plasma armature would cause all of the injected current to flow in the reverse direction in the launcher. Reverse current flow for evaluation purposes will not be a problem as long as its magnitude is well below the primary driving current in the launcher. This reverse current may even help to maintain a compact plasma by slowing the higher conductivity regions at the front of the plasma. By monitoring the response at the B-dot cards to the injected current, the conductivity of the plasma may be evaluated as the launch proceeds. As with the UDESS system, there can be multiple current injection points along the launcher.

5.3 SUMMARY

We have no evidence which suggests that a UDESS will deter secondary armature formation in EM launchers utilizing plasma armatures. Any conductive plasma which is behind the main armature, and in the vicinity of a stage supply feedpoint, appears to be heated to a more conductive state when the stage supply is discharged, thereby creating an immediate secondary. Waiting to fire the DES stage supplies until the full length of the partially ionized plasma has passed the stage supply feeds does not appear to be feasible. A major portion of the entire distance behind the main armature is filled with residual plasma, thereby requiring a significant delay in firing. Subsequent stage supply firing then raises the ionization potential near the feed point to a high level.

For metal armature launches, theoretical DES efficiency should be greater than conventional breech fed EM launchers. We have found no evidence to counter this. Our UDESS prototype implementation simply used too high of a level of breech energy input relative to the DES stage input to accurately assess efficiency improvements.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

From this study, we conclude:

1. A prototype UDESS electromagnetic launcher has been developed and fabricated (Section 3).
2. Methods to evaluate the performance limits for this prototype have been developed and demonstrated (Section 4).
3. The prototype failed to demonstrate the ability to reduce the likelihood of secondary armature formation during laboratory tests (Section 5).
4. The demonstrated ability for controlled energy discharge in the prototype is useful for continuing the advancement of EM launcher technology (Section 5).

Based on these conclusions, we recommend that research on the UDESS system be continued with an emphasis towards evaluating its potential benefits to EM launchers which utilize metal armatures. We recommend that the UDESS system be utilized as a research tool for continued evaluation into plasma armature characterization.